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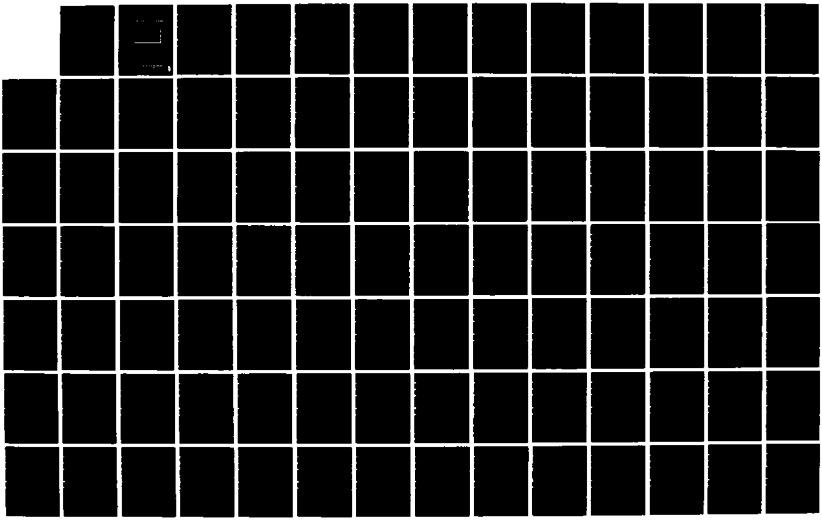

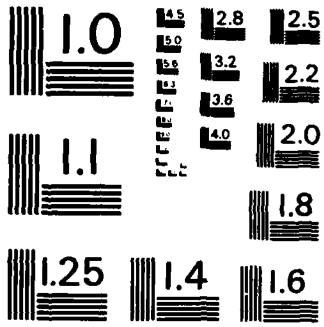
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THE UNIVERSITY OF OKLAHOMA

School of Industrial Engineering
Norman, Oklahoma 73019

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Final Technical Report
Contract No.: N00019-83-~~0237~~ C-0327

on

Performance Models of Testability

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A multi-level maintenance tier testability evaluation model is developed. This model evaluates analytically the testability parameters at the organizational, intermediate, and the depot levels. In addition, it describes three measures of effectiveness of the performance of the multi-level testability system taking into account the imperfections of the diagnostic system (false alarms, Can Not Duplicate, and Retest Okay).

Furthermore, all costs associated with the errors of the diagnostic system are → over

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Performance Models of Testability

Submitted to

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SUMMARY

In recent years automatic fault detection/fault isolation (FD/FI) systems are widely used as maintenance tools for electronic equipment/systems. However, the operational experience with FD/FI systems has not been good because of lacking effective operational testing measures that can express the adequacy of the diagnostic system. The objective of this study was to investigate performance models for the analysis of testabilities of Avionics Systems.

In general, the problem with all known diagnostic measures can be traced to inadequate and ambigious definitions of terms, parameters, and their meanings. In addition, most parameters are defined and determined as if the levels of maintenance have nothing to do with these parameters, which is not always true. Therefore, single and multi-level diagnostic systems are represented by decision trees where testability parameters are accurately and unambiguously defined at each level. Accordingly, a multimaintenance tier testability evaluation model which contains all levels of testability parameters at the organizational, intermediate, and depot levels is developed. In this model three measures of effectiveness of the performance of the multi-level testability systems are developed, and analytical procedures to evaluate these measures are derived, taking into account all problems which may arise from the implementation of automatic diagnostic systems.

The first measure represents the occurence of intermittent and temporary faults as well as the potential of the test equipments to either cause malfunction in the system or not to work properly, while the second measure reflects the failure of the testing system to perform its major objective of detecting and isolating faults when they occur. The above measures represent the accuracy of the diagnostic system and the ability of test equipment at each level to perform within specifications.

The third measure represents the precision of the testability system and the ability of different test equipments at the same or upper levels to repeat the same results according to its tolerances and precisions. This measure covers mainly Can Not Duplicate and Retest Okay at different levels.

Furthermore, new optimization procedures have been developed to aid in the evaluation of reliability, maintainability, and availability of the system. In addition, all costs associated with the errors of the diagnostic system are developed and modeled to express the effectiveness of the diagnostic system. These costs are also used to predict the life cycle cost for the equipment/system, taking into account the actual performance of the diagnostic system and the resulting consequences of its imperfections.

CONTENTS

LIST OF ILLUSTRATIONS

1. INTRODUCTION

1.1 Background

In recent years the development and use of automatic diagnostic systems as maintenance tools for electronic equipment/system has increased significantly. The available advanced technologies in electronics allowed the development of ever-increasingly complex systems and necessitated the development of modular diagnostic concept. Consequently, automation was introduced into the fault diagnostic process at the system, subsystem and equipment levels.

The incorporation of automatic fault detection/fault isolation (FD/FI) systems which uses Built-in-Test (BIT) and/or External Test Equipment (ETE) can be a significant aid to system maintainability and system availability through the automatic detection and isolation of malfunctions without having to resort to time-consuming manual troubleshooting techniques. Furthermore, the manpower and training necessary to support complex system can be reduced.

However, advances in electronic technology have overpaced the technology of efficient and effective fault diagnostic design. Few new procedures or techniques have been developed to aid in the design of cost effective automated fault diagnostic systems which include BIT/ETE systems as part of a comprehensive multi-level maintenance plan. In addition, the operational test and evaluation experience with FD/FI systems has, unfortunately, not been good, lacking an effective operational testing methodology. For this reason, it was virtually impossible to accurately assess a system's real diagnostic capability, let alone its contribition to overall system availability.

Furthermore, the implementation of automatic diagnostic system can produce three types of problems: false alarms, could not duplicate (CNDs), and retest OKays (RTOKs). When the diagnostics indicate a failure, but no system degradation is apparent to the operator, the event is called false alarm. Such failure indications are thought to be caused by momentary excursions of the system outside its set parameters. The major impact of false alarm events is a reduction of operator confidence in the diagnostics, and possibly unnecessary isolation of good units and introducing them to the repair cycle with all consequences. When subsequent maintenance investigation fails to duplicate the condition for which a system has written up, the event is a CND. CNDs may be caused by intermittent failure and they result in the expenditure of resources without valid system repair. A RTOK is a malfunction which, when detected and isolated by the automatic diagnostics at one level of maintenance, is not detectable at a higher level. A possible cause of RTOK events is a lack of vertical testability. Because of the significant effect of false alarm, CNDs, and RTOKs events in life cycle cost, system maintainability and availability, all these events should be carefully defined, studied and included in any study of automatic system diagnostics. In addition, strategies must be developed to minimize these events.

A multi-level maintenance system consists of three levels. The lowest level is organizational, where a faulty system is tested to isolate the line replaceable unit (LRU) that include the faulty module. This LRU is removed from the system, and a spare substituted so the system may resume operation. The faulty LRU is sent ot the shop level where the faulty module or shop replaceable unit is isolated and replaced. The LRU is then returned to the organizational level for standby. The faulty module may be sent to the depot for repair or may be discarded, based on cost of repair versus replacement.

1.2 Related Research

A review of the technical literature shows that most of the work in the field of testability dealt with very special problems, mainly in the area of design of diagnostics, evaluation and assessment of diagnostic system, and cost design characteristics and design guideline for testing systems. In most of the references, only certain testability parameters were considered and defined to fit a very special problem without any effort to relate such parameters to the entire composite diagnostic system, which includes organizational, shop and the depot levels.

As for the problem of designing optimum testing procedures, the search started in the late fifties when Gluss (1959) tackled the problem of having a fault developed in a system consisting of n modules where each one contains several components. He presents two mathematical models to dictate search strategies that will minimize a stipulated cost function. Firstman and Gluss (1960) extend Gluss's work by considering different ways to estimate the probabilities of faults lying in respective modules. A related work by Johnson et al. (1960) discusses the generation of efficient sequential tests procedures by using information theoretic methods to evaluate the amount of information provided by a test. Kletsky (1960) demonstrates the validity of the information theory approach by studying a standard communication receiver, then he proposes a diagnostic procedure to test it. He reports that this method can be adapted to provide diagnostic procedures appropriate to almost any level of maintenance (organizatyion, shop, or depot). Winter (1960) demonstrates the validity of the information theory approach by studying a standard communication receiver, then he proposes a diagnostic procedure to test it. He reports that this method can be adapted to provide diagnostic procedures appropriate to almost any level of maintenance (organization, shop, or depot). Winter (1960) derives necessary conditions in order to find an optimal testing sequence by successive permutations of adjoining units using conditional probabilities and statistical analysis.

Chang (1968) introduces the distinguishability criterion for computing the figure of merits of tests and accordingly derive efficient testing procedures. Cohn and Ott (1971) present a recursive algorithm based on the concept of dynamic programming to specify an adaptive testing procedure that detects a failure and isolates the faulty component while minimizing the expected cost of testing. Butterworth (1972) considers the system which works if K or more of its N components work. He develops a methematical model to derive several rules for finding the optimal sequential policies for series and parallel systems for independent LRUs. Halpern (1974) presents a heuristic simple adaptive sequential testing procedure for the K-out-of-N system with equal cost of all tests. Pieper et al. (1974) develop a step-by-step computerized procedure for generating complete troubleshooting trees which will identify the ssytem's functional unit which is causing observable system malfunction indications. Sheskin (1977, 1979) develops a *probabilistic dynamic programming procedure to determine* the sequence of tests to isolate the group of modules which contains the faulty unit. He also presents a hybrid dynamic programming algorithm to determine the optimum partition of the equipment and the set of tests which should be executed by BIT in order to produce this partition.

Aly (1979) presents a Branch-and-Bound algorithm to solve the problem of the optimum design diagnostics (fault detection and isolation). Although, no computational experience is provided, the algorithm has a great tendency to reduce both the computations and storage burden in comparison and storage burden in comparison to the ones employing dynamic programming. Aly (1980) develops several dominance and reduction rules which improve the performance of his branch-and-bound algorithm. Aly and Elsayedaly (1981) provide a comprehensive computational results for the branch-and-bound algorithm and also show its superiority over other methods developed based on dynamic programming.

The literature rarely addresses the problem of evaluating and assessing diagnostic system. Emphasis on such works is to find a valid and reliable procedure to check the effectiveness of BIT/TE system, or to evaluate FD/FI systems. Poliska et al. (1979) studies a diagnostic system which consists of BIT and/or external test equipment in order to determine the measures and figures of merit that are required to determine the adequacy of the system. Simple mathematical models are used to evaluate the figure of merits using the scoring factor weights. Conley (1980) presents a Failure Modes and Effects Analysis (FMEA) procedure to be used on a complex digital data system where the FD/FI is specified for the system. Tuttle and Loveless (1980) study the reliability of the BIT/ETE system as a function of the complexity, physical characteristics, and functional characteristics of the BIT/ETE used in support of a system. They also study the impact on the operation of the prime equipment due to the failure modes of BIT/ETE using correlation analysis. Horkovich (1981) discusses the importance of developing an efficient methodology to evaluate fault detection/fault isolation systems taking into consideration the overall system Mean-Time-To-Repair (MTTR), CND, and RTOK rates. Linden (1981) studies the effectiveness of BIT/ETE and discusses approaches/trends towards highly automated diagnostics. False alarms, CNDs, and RTOKs are explained and their role in determining the effectiveness of BIT/ETE systems and the implication of the CNDs, RTOKs, and false alarms which are inherent in such systems. He uses the expected number of removals that occur per single prime system failure as a measure of effectiveness of the system and how effectively the associated test equipment is performing its designated job of fault detection and isolation. Aly and Bredeson (1983) discuss many aspects of diagnostic procedures and checked some predictions parameters for their effect on a reliable system.

In the area of cost characteristics and design guidelines for testing systems Gaertner (1974) describes the design of the BIT circuitry for tactical FM radios considering functional and physical characteristics of the BIT system. Levy et al. (1976) study test procedures and specifications during the depot repair cycle. They develop a method for identifying key maintenance decisions and optimizing tests and test decisions in order to minimize support costs. Biegel and Bulcha (1978, 1979) study the multilevel modularization/partitioning of large electronic networks subject to physical MTTR and availability constraints in order to minimize the life cycle cost. They develop a generalized procedure that is capable of doing any number of levels of modularization. Bogard (1980) studies the logistic support cost characteristics of BIT/ETE in order to develop guidelines and relationships for use in the development phase of an Air Force electronic equipment program to estimate operation and support costs associated with various types of testers and test subsystems. Heckelman et al. (1981) investigates the effects of architecture, functional partitioning, and module and component features on micro-programmable self-diagnosing capabilities of digital processors. These results are then used to create a set of design guidelines for designing self-diagnosing, fault-tolerant, highly reliable microprocessors, namely monolithic and bit-slice processors using LSI devices. Aly and McDonald (1983) develop a minimum expected cost diagnostic procedure based on the combined costs of packaging and testing at the organizational and intermediate levels.

From the above survey, non of the references address the optimization of the entire multi-level system, taking into account the effectiveness and reliability of organizational built-in-test/automatic test equipment, shop test, and depot test as a function of the physical and functional characteristics of these tests as well as the overall fault detection/fault isolation (FD/FI) of the system. Even though statistical methods are utilized for some problems, very few of them consider a realistic life cycle cost of the system which takes into account the penalties and costs associated with all errors of the diagnostic system at all levels of repair. Also, all figures of merit are inconsistent to be effective in the design of the prime system as a result of the ambiguities, and differences in interpretation of different testability parameters.

2. TESTABILITY PARAMETERS

In this section, problems and critiques of testability parameters are presented and discussed. Then, a general testability model for any level of repair is used to define more accurate and unambiguous testability parameters. Accordingly, measures of effectiveness of the multi-level testability systems are developed and analytical procedures to evaluate these measures are derived.

2.1 Critique of Testability Parameters

In general, the problem with all known testability parameters can be traced to inadequate and ambiguous definitions of terms, parameters and their meanings. Take for example the three definitions for Fraction of Faults Detected (FFD). In particular consider the terms: Q_{BDF} (quantity of faults detected by BIT/ETE), Q_{FD} (quantity of faults detected) and Q_{VDF} (quantity of faults detected through use of defined means). Q_{BDF}, Q_{VDF}, and Q_{FD} have in some instances been calculated taking into account only detections caused by actual faults. In addition, when we define Q_{BDF}, Q_{FD}, and Q_{VDF} do we mean all possible faults or the faults which will occur over a period of system operating life (in accord with failure rates)?

Furthermore, it is observed that most parameters are defined and determined as if the levels of maintenance have nothing to do with them and their values, which is not true since test tolerances are different at different levels.

2.2 General Testability Model for Any Level of Repair

At any level of repair ℓ (organizational, intermediate, or depot) the testability system can be modeled as shown in Figure 2.1. A diagnostic group, which is to be tested by the available test equipment at this level, contains n_ℓ replaceable units (RU), with each RU_i containing m_i sub-replaceable units (SU).

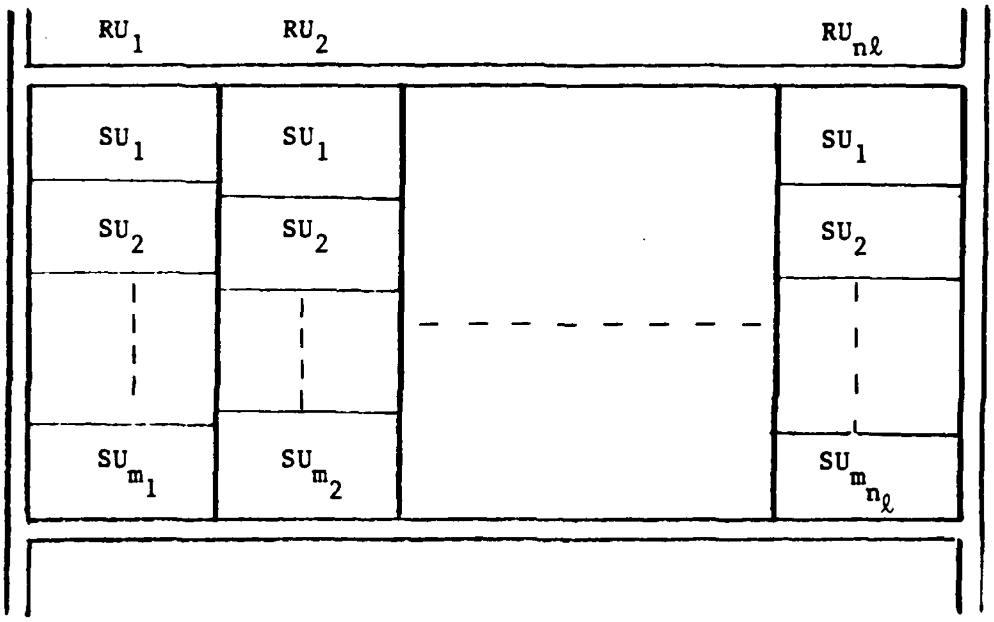

Figure 2.1 A Diagnostic Group

This model is general enough to accomodate the testability systems at any level. At the organizational level, the diagnostic group is the prime equipment, the replaceable unit is the Line Replaceable Unit (LRU), the subreplaceable unit is the module, and the test equipment is the BIT/ATE system. Also, $n_o = N$ where N is the number of LRU's in the prime equipment.

At the intermediate level, the diagnostic group is the LRU which has been isolated at the organizational level, say LRU_i, the replaceable unit is the module, the subreplaceable unit is the component or part and the test equipment used at this level is the external test equipment (ETE). Also, $n_I = M_i$, where M_i is the number of modulas in the LRU_i.

At the depot, the diagnostic group is the module which has been isolated at the intermediate level, say module k, the replaceable unit is the component or unit and the test equipment is the manual or semiautomatic test equipment at the depot. Furthermore, $n_D = U_{ki}$, where U_{ki} is the number of components in module k of LRU_i.

2.3 General Testability Procedures at Any Level of Repair

A general testability procedure at any level ℓ (organizational, intermediate, depot) is depicted in Figure 2.2 where the diagnostic system can be in one of the following states:

a. **Successful Performance**

   The diagnostic system correctly detects and isolates the faulty RU if a fault exists, or the diagnostic system reports no failure when the diagnostic group is fault free.

b. **Failure to Report**

   A faulty diagnostic group is introduced at level ℓ. However, test equipment could not report or verify the failure.

c. **Failure to Isolate RU**

   A faulty diagnostic group is introduced to level ℓ, where the failure is verified. However, the test equipment fails to isolate the faulty RU and reports no failure instead.

d. **False RU Isolation**

A faulty diagnostic group is introduced to level ℓ where test equipment verified its failure. However, it isolates a good RU instead of the faulty one.

e. **False Report**

A good diagnostic group is introduced to level ℓ. However, test equipment mistakenly reported a failure (false alarm) and isolated a good RU.

f. **Can Not Duplicate at level ℓ (CND_ℓ)**

A god diagostic group is introduced to level ℓ where test equipment reports a failure (false alarm). However, in the isolation process no faulty RU is found.

2.3.1 Definitions

Let

N = number of LRU's in the prime equipment

M_j = number of modules in LRU_j

U_{ki} = number of components or units in module k of LRU_j

$$\ell = \text{level of repair, } \ell = \begin{cases} O & \text{organizational} \\ I & \text{intermediate} \\ D & \text{depot} \end{cases}$$

n_ℓ = number of replaceable units (RU) in the diagnostic group at level ℓ

$\lambda_{\ell i}$ = failure rate of RU_i at level ℓ

$P(af_i)_\ell$ = proportion of all possible faults in RU_i ($i=1,\ldots,n_\ell$), which are addressable by the test equipments at level ℓ

$P(d_i)_\ell$ = proportion of all addressable faults in RU_i which can be detected by the test equipments at level ℓ

$P(FI_i)_\ell$ = probability that the test equipments at level ℓ will correctly isolate the failure to i or less RU after detecting the failure, given that the diagnostic group at level ℓ is actually faulty

$P(MB)_\ell$ = probability that any good RU at level ℓ will be mistakenly isolated by the test equipments, given that the diagnostic group at this level is actually faulty

$P(FA)_\ell$ = probability that the test equipments at level ℓ report a failure given that the diagnostic group is not faulty

$P(MG)_\ell$ = probability that any good RU at level ℓ is mistakenly isolated by the test equipment after the occurrence of a false alarm at this level

2.3.2 Failure of Diagnostic Groups

Let $P(F)_O$ be the probability of equipment failure (at the organizational level), $P(F)_I$ be the probability of introducing a faulty LRU to the intermediate level, and $P(F)_D$ be the probability of introducing a faulty module to the depot.

Assuming that only one faulty unit can exist within the prime equipment undergoing test. Let $P(f_i)_o$ be the probability of failure of LRU; at the organizational level in operating/mission time t, then

$$P(F)_O = 1 - \text{Prob. [equipment is good]} \tag{2.1}$$

but, Prob. [equipment is good] = Prob. [LRU_1 is good and LRU_2 is good... and LRU_N is good]

$$= P[LRU_1 \text{ is good}] \cdot P[LRU_2 \text{ is good}] \ldots P[LRU_N \text{ is good}]$$

$$= [1-P(f_1)_O] \cdot [1-P(f_2)_O] \ldots [1-P(f_N)_O]$$

$$= \prod_{i=1}^{N} [1-P(f_i)_O]$$

substituting in equation 2.1, then

$$P(F)_O = 1 - \prod_{i=1}^{N} [1-P(f_i)_O] \tag{2.2}$$

But since after initial wear-in, when the occurrences of failures are essentially random, electronic LRU's and modules often demonstrate failure characteristics that are described by the negative exponential distribution. Then,

$$P(f_i)_0 = 1 - e^{-t\lambda_{oi}}$$

and t = operating/mission time of any LRU_i substituting in equation 2.2, then,

$$P(F)_0 = 1 - \prod_{i=1}^{N} e^{-t\lambda_{oi}}$$

and from figure 2.2

$$P(F)_I = \frac{P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0}{P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 + P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0}$$

$$P(F)_D = \frac{P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I}{P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I + P(F)_I \cdot P(FD)_I \cdot P(FL_i)_I + [1-P(F)_I] P(FA)_I \cdot P(WI_i)_I}$$

2.3.3 Actual Fault Detection Capability of the Test Equipment

The actual fault detection capability of the test equipment at any level ℓ should consider both *faults which are addressable* and those which are not addressable by the test equipment. In addition, all addressable faults should be specified to those faults which can occur during the diagnostic group operating life. Let $P(af_i)_\ell$ be the proportion of all possible faults in the RU_i at level ℓ which are addressable by the test equipment, $P(d_i)_\ell$ be the proportion of all addressable faults in RU_i which can be detected by the test equipment at level ℓ, and $P(fd_i)_\ell$ be the probability [test equipments will detect a fault in RU_i at level ℓ $|RU_i$ is faulty]. Then,

$$P(fd_i)_\ell = P(d_i)_\ell \ P(af_i)_\ell$$

Also let $P(RU_i|f)_\ell$ be the probability that a failure is in RU_i at level ℓ given that a failure exists, then

$$P(RU_i|F)_\ell = P[RU_i \text{ is faulty at level } \ell | \text{diagnostic group is faulty}]$$

$$= \frac{\lambda_{\ell i}}{\sum_{i=1}^{n_\ell} \lambda_{\ell i}}$$

where $\lambda_{\ell i}$ is the failure rate of RU_i at level ℓ, hence

$\lambda_{\ell i}$ = total failure rate of all m_i SU in RU_i at level ℓ

since,

$P(FD)_\ell$ = prob. [test equipment will detect a fault at level ℓ | diagnostic group is faulty]

then,

$$P(FD)_\ell = \sum_{i=1}^{n_\ell} P(RU_i|f)_\ell \; P(fd_i)_\ell$$

In this case $P(FD)_\ell$ is the actual detection capability of the test equipment at level ℓ when a fault exists in the diagnostic group introduced to this level.

2.3.4 Actual Fault Isolation Capability of the Test Equipments

a. Correct Isolation

The correct isolation capability of a diagnostic system can be defined by $P(FI_i)_\ell$ where

$P(FI_i)_\ell$ = prob. [failure will be isolated to i or less RU at level ℓ | a fault is detected and the diagnostic group is faulty]

b. Misassignment

Assuming that any good RU at any level has the same chance to be mistakenly isolated (misassignment), let

$P(MB)_\ell$ = prob. [any good RU at level ℓ will be mistakenly isolated | diagnostic group is faulty]

Since misassignment can occur independently of each other in the $n_\ell - 1$ good RU at level ℓ, then the probability of i misassignments is a discrete random variable with a binomial probability distribution such that if

$P(FL_i)_\ell$ = probability [i or less good RU will be mistakenly isolated at level ℓ | a fault is detected and the diagnostic group is faluty], $i \neq 0$

then,

$$P(FL_i)_\ell = \sum_{k=1}^{i} \binom{n_\ell - 1}{k} (P(MB)_\ell)^k (1-P(MB)_\ell)^{n_\ell - k - 1}$$

When the specification combines the isolation of good RU's and no isolation of any RU together then

$$P(FL_i)_\ell = 1-P(FI_i)_\ell$$

c. **No Isolation**

Probability of no isolation of any RU good or faulty/diagnostic group is faulty at level ℓ, $P(NI)_\ell$, can be computed using $P(FI_i)_\ell$ and $P(FL_i)_\ell$ where,

$$P(NI)_\ell = 1 - P(FL_i)_\ell - P(FI_i)_\ell$$

2.3.5 False Alarm

False alarm can be measured by $P(FA)_\ell$ where

$P(FA)_\ell$ = probability [test equipment detects a failure at level ℓ | diagnostic group is good] = prob. [false alarm at level ℓ]

As a result of the false alarm, false isolation can occur which can be measured by $P(WI_i)_\ell$ and $P(MG)_\ell$ where

$P(WI_i)_\ell$ = probability [i or less good RU's will be isolated at level ℓ | a fault is detected and the diagnostic group is good], $i > 1$

$P(MG)_\ell$ = prob. [any good RU will be mistakenly isolated at level ℓ | diagnostic group is good]

Since false isolation can occur independently of each of the n_ℓ good RU's at level ℓ, then the probability of the false isolation of i RU's is a discrete random variable with a binomial probability distribution such that

$$P(WI_i)_\ell = \sum_{k=1}^{i} \binom{n_\ell}{k} (P(MG)_\ell)^k (1-P(MG)_\ell)^{n_\ell - k}, \quad i > 1$$

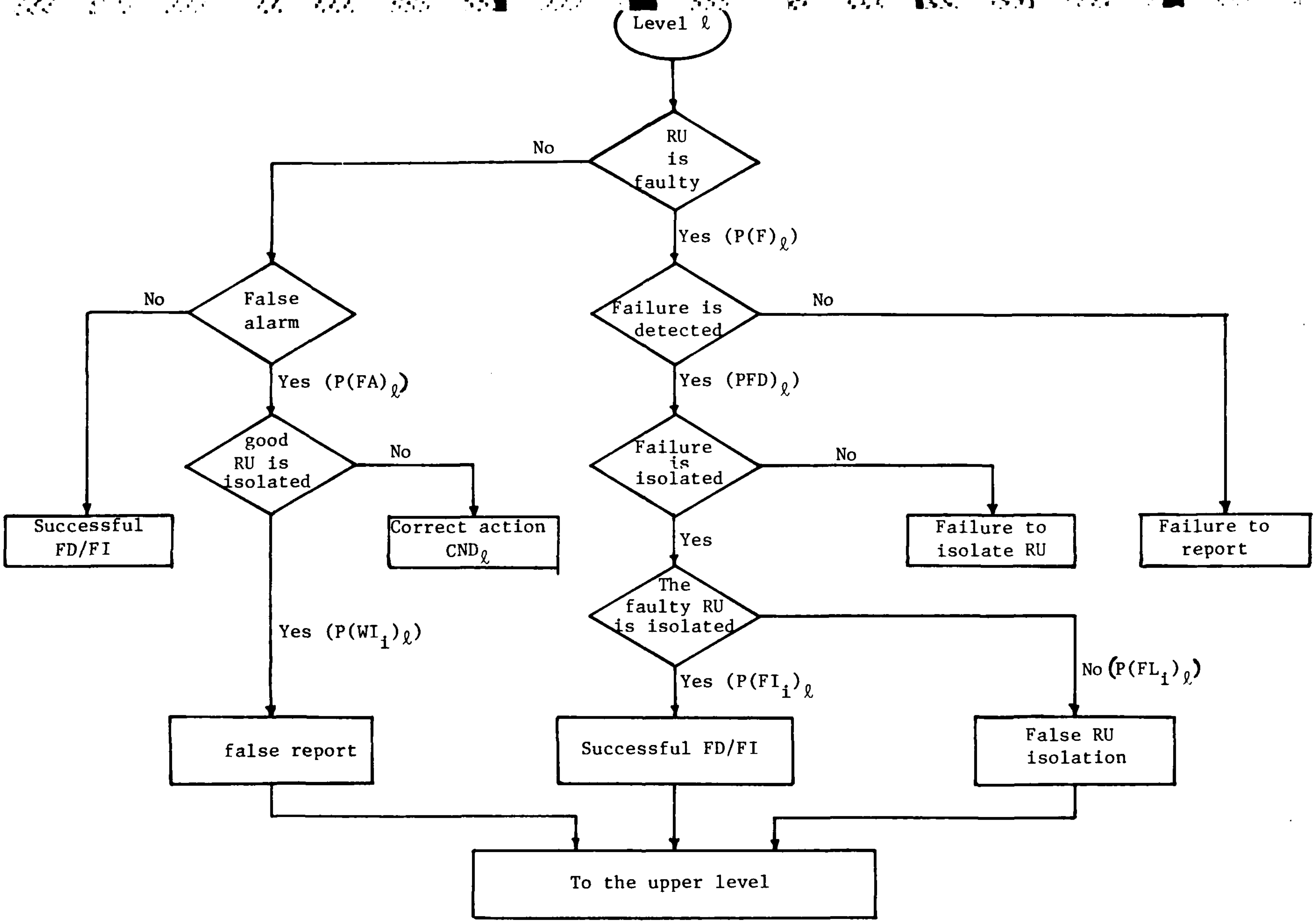

Figure 2.2: General Testability Procedures at any Level ℓ

The CND at level ℓ can be measured by $P(CND)_\ell$, where

$$P(CND)_\ell = \text{Prob. [isolating no RU at level } \ell \mid \text{false alarm]}$$
$$= \binom{n_\ell}{0} (P(MG)_\ell)^0 (1-P(MG)_\ell)^{n_\ell}$$
$$= (1-P(MG)_\ell)^{n_\ell}$$

2.4 Measures of Multi-Level Diagnostic System Effectiveness

Since the existence of many different parameters leads to problems in system optimization, it would seem to be desirable to be able to logically group more than a parameter into a single measure. Several attempts at this have been tried. All have been less than entirely valid from a mathematical/engineering standpoint. For example, many automatic fault detection/fault isolation systems use only one figure of merit FD/FI, as an indication of the diagnostic system capability. For example, 90%/80% means 90% of those malfunctions addressable by the FD/FI capability are detected and of those detected 80% are isolated. Since the percentage of faults detected and isolated are considered independent, it can be concluded that 72% of the addressable functions can be isolated. This figure is misleading since it disregards the undetected faults, it ignores the possibility that fault detection is not necessarily independent of fault isolation, and it is ambiguous with respect to how false alarms, false isolation, and CND are to be interpreted.

In addition, automatic detection and isolation equipment in the form of built-in-test equipment and removable/replaceable modules were primarily introduced to sophisticated weapon systems in order to improve and support the availability and maintainability of these systems, decrease the maintenance burden and provide an alternative to the rising costs of training, high personnel turnover, and the increase in resources necessary for system support. However, the experience with those diagnostic systems has not lived up to expectation, lacking an effective operational testing methodology which can accurately assess the system's real diagnostic capability, and its contribution to overall weapon system availability.

Furthermore, when selecting a measure of effectiveness we should keep in mind that the measure will have little value without certain essential characteristics. Probably the most important characteristic is that the measure be expressed quantitatively. We should be able to reduce it to a number such that comparisons between alternative designs can be made. Further, the measure we choose must have a basis in physical reality. Thus, it should be descriptive of the real problem, neither exaggerated nor over-simplified. Yet at the same time the measure should be simple enough to allow for mathematical manipulation.

In this section, three measures of effectiveness of the multi-level diagnostic system are presented. They are derived from the actual system requirements in order to accurately represent the system's real diagnostic capability. They are called α, β, and γ errors.

a. **False Removal (α error)**

At any level, if the diagnostic group is not faulty, then the diagnostic system should not report or isolate any good RU. If it does report/isolate a good RU where no failure exists in the diagnostic group, the diagnostic system commits α error. This error represents the occurence of intermittent and temporary faults as well as the potential of the test equipment either to cause malfunction in the diagnostic group or to work improperly.

b. **Failure to Diagnose (β error)**

At any level, if the diagnostic group is faulty, then the main objective of the diagnostic system is to detect and isolate the faulty

RU. So, if a fault occurs and the test equipment fails to report or isolate the faulty RU or it isolates a good RU instead, then β error is committed. This error reflects and represents the failure of the testing system to perform its major objective of detecting and isolating faults when they occur.

c. **Lack of Precision (γ error)**

If the diagnostic group at any level is not faulty, the test equipment at this level should report no failure or isolate no good RU -- a correct action. However, if that occurs after mistakingly reporting a failure or isolating an RU either at the same level or at any lower levels, then γ error is committed. Simply, this error is the CND's and RTOK's at different levels.

α and β errors represent the accuracy of the diagnostic system and the ability of test equipment at each level to perform accurately according to specifications without errors.

A γ error represents the precision of the testability system and the ability of different test equipment at the same level or different levels to repeat the same results according to its tolerance and precision.

2.5 Testability Effectiveness Measures at level ℓ

α, β and γ errors at any level ℓ (organizational, intermediate, or depot) can be developed using the decision tree in Figure 2.2 as follows:

α_ℓ = P[false RU detection and/or isolation at level ℓ | diagnostic group is good]

β_ℓ = P[failure to detect and/or isolate the faulty RU at level ℓ | diagnostic group is faulty]

γ_ℓ = P[correct action of not isolating a good RU at level ℓ after reporting its failure | diagnostic group is good]

δ_ℓ = P[successful performance of the test equipment at level ℓ]

where,

α_ℓ = P[false RU isolation|diagnostic group is good]

$= P(WI_i)_\ell \; P(FA)_\ell \; [1-P(F)_\ell]$

β_ℓ = P[failure to report] + P[failure to isolate RU] + P[false isolation]

$= P(F)_\ell - [P(F)_\ell \; P(FD)_\ell] + [P(F)_\ell \; P(FD)_\ell - P(F)_\ell \; P(FD)_\ell \; P(FL_i)_\ell - P(F)_\ell$

$P(FD)_\ell \; P(FI_i)_\ell] + P(F)_\ell \; P(FD)_\ell \; P(FL_i)_\ell$

$= P(F)_\ell - P(F)_\ell \; P(FD)_\ell \; P(FI_i)_\ell$

$= P(F)_\ell [1-P(FD)_\ell \; P(FI_i)_\ell]$

$\gamma_\ell = CND_\ell$

$= [1-P(F)_\ell] \; P(FA)_\ell - [1-P(F)_\ell] \; P(FA)_\ell \; P(WI_i)_\ell$

$= [1-P(F)_\ell] \; P(FA)_\ell \; [1-P(WI_i)_\ell]$

δ_ℓ = P[isolating the faulty RU|diagnostic group is faulty]

+P[report no failure|diagnostic group is good]

$= 1-P(F)_\ell - [1-P(F)_\ell] \; P(FA)_\ell + P(F)_\ell \; P(FD)_\ell \; P(FI_i)_\ell$

$= [1-P(F)_\ell] \; [1-P(FA)_\ell] + P(F)_\ell \; P(FD)_\ell \; P(FI_i)_\ell$

2.5.1 Special Case

When the depot repair cycle is perfect, as in Figure 2.3, then for every faulty module, the faulty component will be isolated and for every good module, no isolation results. Also, the above formulas will remain the same except that $P(WL_i)_D = 0$ and $P(FI_i)_D = 1$

hence,

$\alpha_D = 0$

$\beta_D = P(F)_D \cdot [1-P(FD)_D]$

$\gamma_D = [1-P(F)_D] \cdot P(FA)_D$

$\delta_D = P(F)_D \cdot P(FD)_D + [1-P(F)_D] \cdot [1-P(FA)_D]$

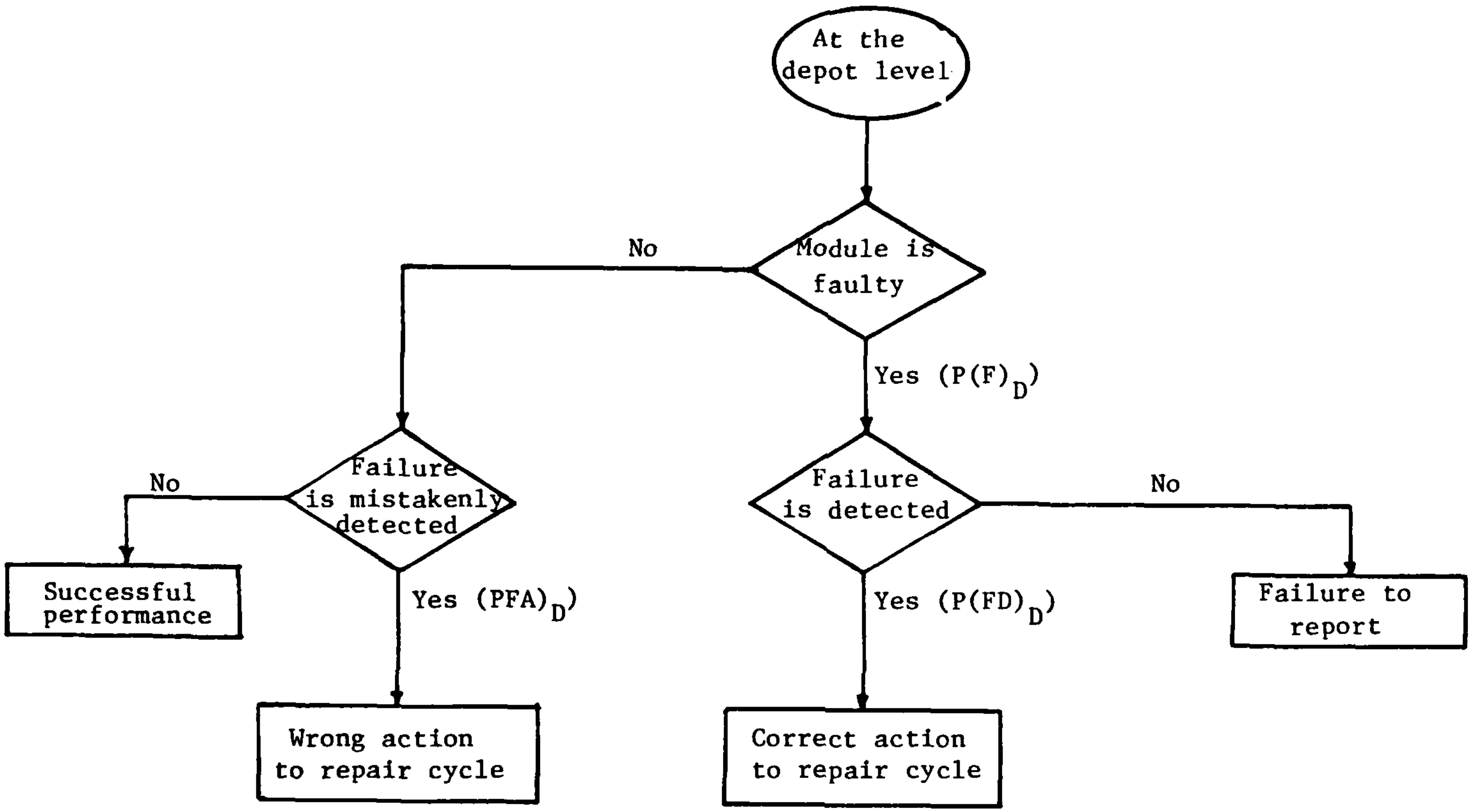

Figure 2.3: Testability Procedures at a Depot with Perfect Repair Cycle

2.6 Testability Procedures for the Organizational/Intermediate System

If the major concern is with the testability at the organizational and intermediate levels as if they are one unit, then the testability system can be presented as in Figure 2.4. The states of this composite system are different from studying each level separately. Accordingly new parameters are considered and some other parameters are redefined to fit the new system. The diagnostic system can be in one of the following states:

a. **Failure to report (organizational)**

The prime equipment is faulty. However, the BIT/ATE at the organizational level reports no failure.

b. **Failure to report (intermediate)**

The prime equipment is faulty and the faulty LRU is isolated at the organizational level. However, ETE at the intermediate level reports no failure in the isolated faulty LRU.

c. **Failure to isolate LRU**

The prime equipment is faulty and the BIT/ATE detects a failure at the organizational level. However, it fails to isolate any LRU.

d. **Failure to isolate module**

The prime equipment is faulty and the faulty LRU is isolated at the organizational level. However, in the intermediate level, ETE verifies the LRU failure but fails to isolate any module.

e. **Successful FD/FI (organizational/intermediate system)**

Isolating the faulty module if the prime equipment is faulty or reporting no failure if the prime equipment is fault free.

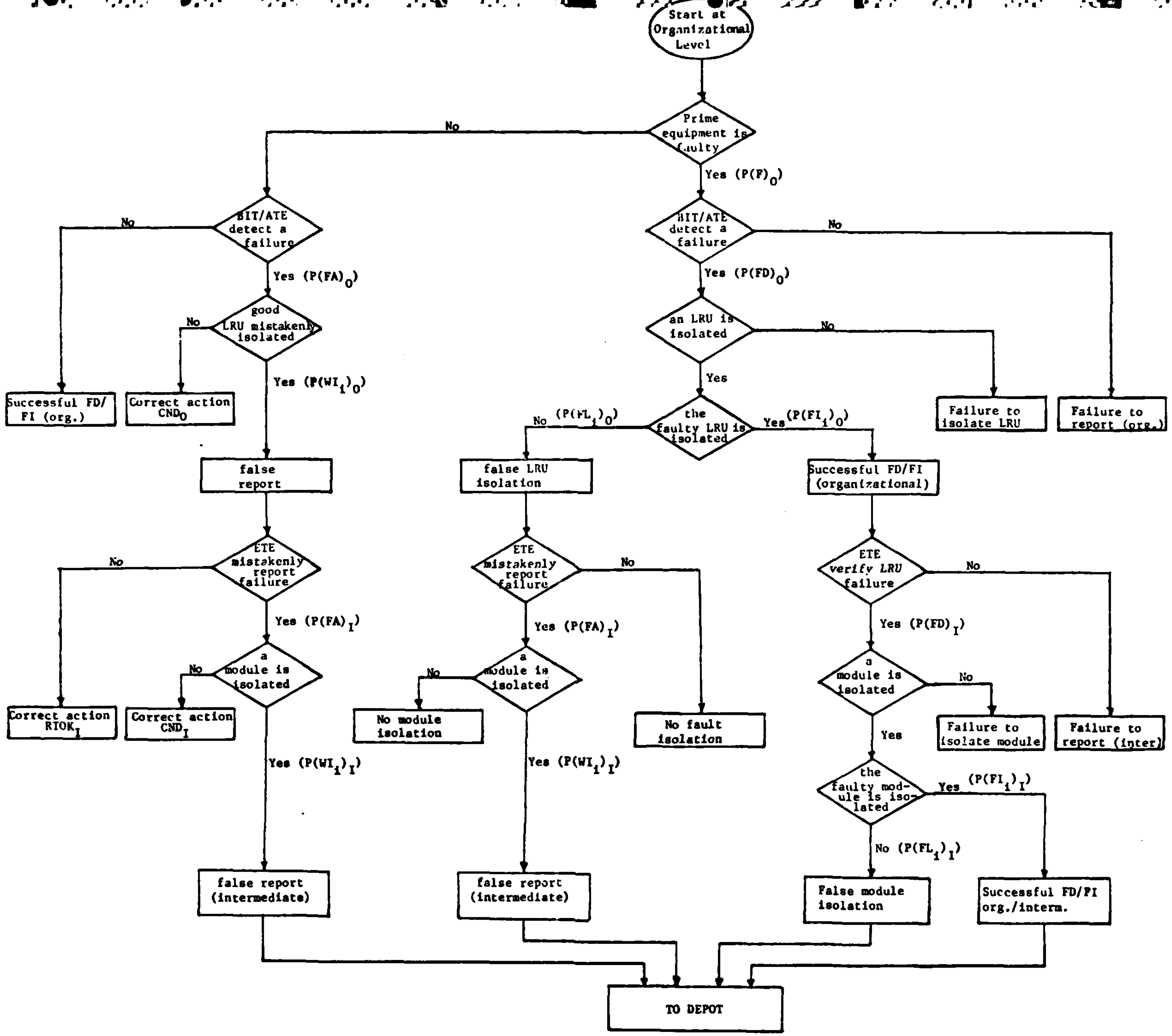

Figure 2.4 Testability Procedures for the Composite Organizational/Intermediate System

f. **False module isolation**

The prime equipment is faulty and the faulty LRU is isolated at the organizational level. However, in the intermediate level a good module is isolated instead of the faulty one.

g. **False Report (intermediate)**

1) The prime equipment is faulty, a good LRU is isolated at the organizational level. In the intermediate level, ETE indicate a failure in the isolated good LRU and isolate a good module.

2) The prime equipment is good, and a good LRU is isolated at the organizational level, as a result of a false alarm. In the intermediate level, ETE indicate a failure in the isolated good LRU and isolate a good module.

h. **No Fault isolation**

The prime equipment is faulty, a good LRU is isolated at the organizational level. In the intermediate level, ETE indicate no failure in the isolated good LRU.

i. **No module isolation**

The prime equipment is faulty, a good LRU is isolated at the organizational level. In the intermediate level, ETE indicate a failure in the isolated good LRU but it isolates no module.

j. **Can Not Duplicate (organizational level) CND**

The prime equipment is good, BIT/ATE reports a failure at the organizational level (false alarm). However, it isolates no LRU.

k. **Can Not Duplicate (intermediate level) CND_I**

The prime equipment is good, a good LRU is isolated as a result of false alarm. In the intermediate level, ETE indicates a failure in the isolated good LRU. However, it isolates no module.

1. Re-Test OK (intermediate level) $RTOK_I$

The prime equipment is good, a good LRU is mistakingly isolated as a result of false alarm. However, in the intermediate level, ETE reports no failure in the isolated LRU.

2.7 Testability Effectiveness Measures for the Organizational/Intermediate System

α, β and γ errors for the organizational/intermediate system are developed using the decision tree in Figure 2.4 as follows:

α_{OI} = P[false report and/or isolation|equipment is good]

β_{OI} = P[failure to correctly detect and/or isolate the faulty unit|equipment is faulty]

γ_{OI} = P[correct action of not isolating LRU and/or module after isolating a good LRU]

δ_{OI} = P[successful performance of the diagnostic system in the organizational and intermediate as a whole]

where,

α_{OI} = P[false report (intermediate)]

$$= [1-P(F)_0]\cdot P(WI_i)_0\cdot P(FA)_0\cdot P(FA)_I\cdot P(WI_i)_I$$

β_{OI} = P[failure to report (org.)] + P[failure to report (int.)] + P[failure to isolate LRU] + P[failure to isolate module] + P[false module isolation] + P[false report (intermediate)] + P[no fault isolation] + P[no module isolation]

$$\begin{aligned}
&= [P(F)_0 - P(F)_0\cdot P(FD)_0] + [P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0 - P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0 \\
&\quad \cdot P(FD)_I] + [P(F)_0 + P(FD)_0 - P(F)_o\cdot P(FD)_0\cdot P(FI_i)_0 - P(F)_0\cdot P(FD)_0 \\
&\quad \cdot P(FL_i)_0] + [P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0\cdot P(FD)_I - P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0\cdot P(FI_i)_I \\
&\quad \cdot P(FI_i)_I - P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0\cdot P(FD)_I\cdot P(FL_i)_I] + [P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0 \\
&\quad \cdot P(FD)_I\cdot P(FL_i)_I] + [P(F)_0\cdot P(FD)_0\cdot P(FL_i)_0\cdot P(FA\ _I\ P(WI_i)_I] + [P(F)_0 \\
&\quad \cdot P(FD)_0\cdot P(FL_i)_0 - P(F)_0\cdot P(FD)_0\cdot P(FL_i)_0\cdot P(FA)_I] + [P(F)_0\cdot P(FD)_0\cdot P(FL_i)_0 \\
&\quad \cdot P(FA)_I - P(F)_0\cdot P(FD)_0\cdot P(FL_i)_0\cdot P(FA)_I\cdot P(WI_i)_I]
\end{aligned}$$

$$\beta_{OI} = P(F)_0 - P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0\cdot P(FD)_I\cdot P(FI_i)_I]$$

$$\gamma_{OI} = CND_0 + CND_I + RTOK_I$$
$$= [[1-P(F)_0]\ P(FA)_0 - [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0] + [[1-P(F)_0]\ P(WI_i)_0$$
$$\cdot P(FA)_0 \cdot P(FA)_I - [1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I \cdot P(WI_i)_I] + [[1-P(F)_0]$$
$$\cdot P(WI_i)_0 \cdot P(FA)_0 - [1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I]$$
$$\gamma_{OI} = [1-P(F)_0]\ P(FA)_0 - [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I$$
$$\delta_{OI} = P[\text{isolating the faulty module} \mid \text{prime equipment is faulty}]$$
$$+ P[\text{reporting no failure} \mid \text{prime equipment is good}]$$
$$= P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I + [1-P(F)_0] \cdot [1-P(FA)_0]$$

2.8 Testability Procedures for the Organizational/Intermediate/Depot System

In this case the major concern is with the testability at the organizational/intermediate/depot levels as if they are one system. This testability system is presented in Figure 2.5. Some of the states of this system are exactly the same as the ones in section 2.6. Among them are failure to report (organizational), failure to isolate LRU, failure to report (intermediate), failure to isolate module, no faulty isolation, no module isolation, CND_0, CND_I and $RTOK_I$. In addition the system can be in one of the following states:

a. **Failure to report (depot)**

The prime equipment is faulty, the faulty LRU is isolated at the organizational level, and the faulty module is isolated at the intermediate level. However, test equipment at the depot reports no failure in the isolated faulty module.

b. **Failure to isolate units**

The prime equipment is faulty, the faulty LRU and faulty modules are correctly isolated at the organizational and intermediate levels. However, in the depot, module failure is verified but no unit is isolated.

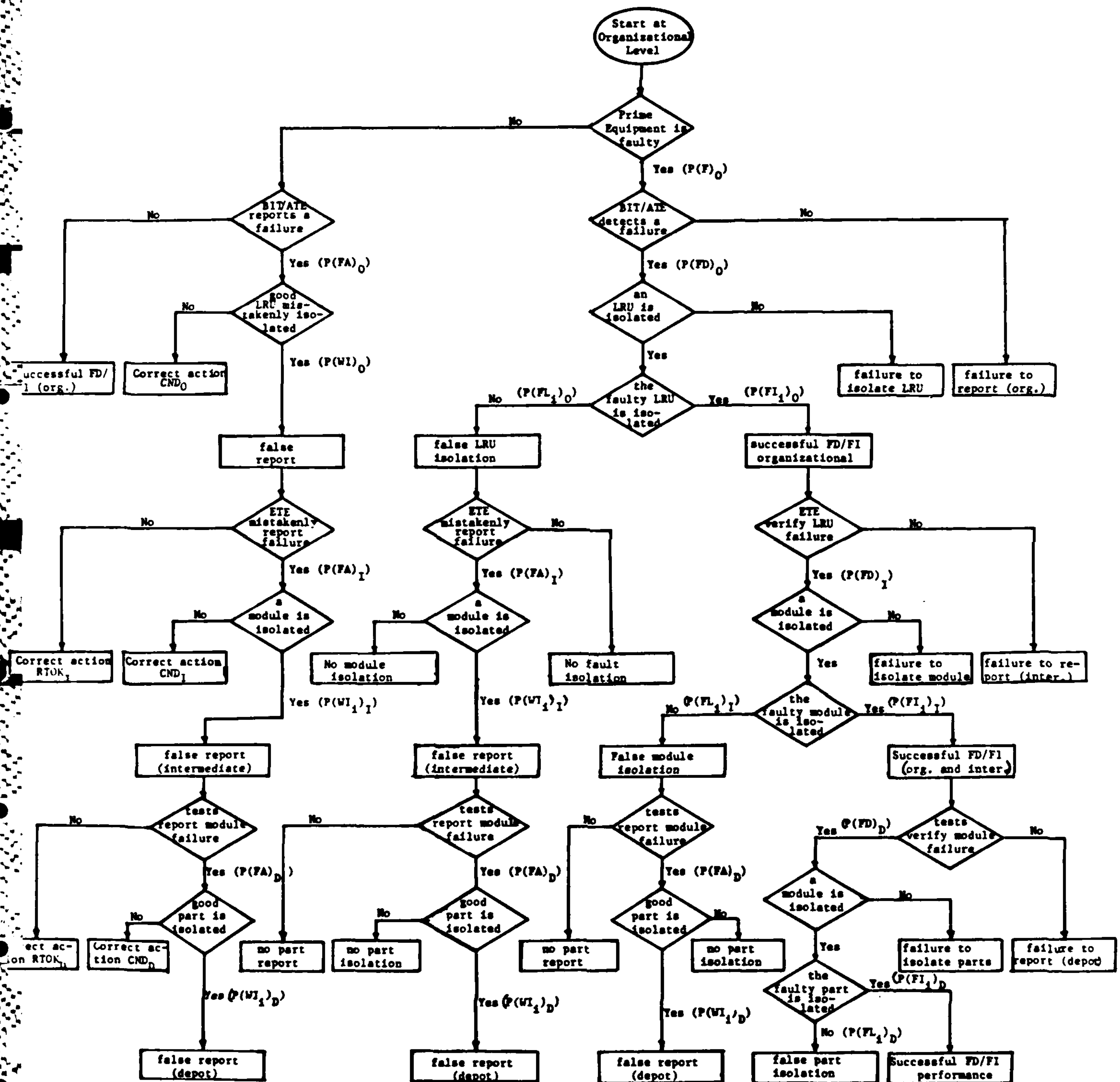

Figure 2.5 Testability Procedures for the Composite Organizational/ Intermediate/Depot System

c. **Successful FD/FI (organizational/intermediate/depot) system**

Isolating the faulty component/unit at the depot if the prime equipment is faulty, or reporting no failure at the organizational level if the prime equipment is fault free.

d. **False Unit Isolation**

The prime equipment is faulty, the faulty LRU and faulty modules are isolated at the organizational and intermediate levels. However, in the depot a good unit is isolated instead of the faulty one.

e. **No Unit Report**

The prime equipment is faulty, a good module is isolated at the intermediate level either after isolating the faulty LRU or isolating a good LRU at the organizational level. Then, tests at the depot report no module failure.

f. **No Unit Isolation**

The prime equipment is faulty, a good module is isolated at the intermediate level either after isolating a good or the faulty LRU at the organizational level. However, tests at the depot report module failure but fail to isolate any units.

g. **False Report (depot)**

A good module is introduced to the depot (as a result of either false module isolation, or false report in the intermediate level) where tests report module failure and isolate good units.

h. **Can Not Duplicate (depot) CND_D**

The prime equipment is good, a good module is introduced to the depot as a result of module false report at the intermediate level. However, tests at the depot report module failure, then isolate no units.

i. **Re-Test OK (depot) $RTOK_D$**

The prime equipment is good, a good module is introduced to the depot as a result of module false report at the intermediate level. However, tests at the depot report no failure.

2.9 Testability Effectiveness Measures for the Organizational/Intermediate/Depot System

α, β, and γ errors for the organizational/intermediate/depot system are derived using the decision tree in Figure 2.5 as follows:

α = P[false report and/or isolation | prime equipment is good]

β = P[failure to detect and/or isolate the faulty unit | prime equipment is faulty]

γ = P[correct action of not isolating LRU, module and/or unit after mistakingly detecting and/or isolating a good LRU or module]

δ = P[successful performance of the diagnostic system as a whole]

$$\alpha = [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot P(WI_i)_D$$

$$\beta = P(F)_0 - [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_i)_I \cdot P(FD)_D \cdot P(FI_i)_D]$$

$$\begin{aligned}
\gamma = {} & [1-P(F)_0]\ P(FA)_0 \cdot [1-P(WI_i)_0] + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot [1-P(FA)_I] + \\
& [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot [1-P(WI_i)_I] + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \\
& \cdot P(FA)_I \cdot P(WI_i)_I \cdot [1-P(FA)_D) + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \\
& \cdot P(FA)_D \cdot [1-P(WI_i)_D] \\
= {} & [1-P(F)_0]\ P(FA)_0 \cdot [1-P(WI_i)_0 + P(WI_i)_0 - P(WI_i)_0 \cdot P(FA)_I] + [1-P(F)_0] \\
& \cdot P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot [1-P(WI_i)_I + P(WI_i)_I \cdot P(FA)_D] + \\
& [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot [1-P(WI_i)_0] \\
= {} & [1-P(F)_0]\ P(FA)_0 \cdot [1-P(WI_i)_0]\ P(FA)_I + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \\
& [1-P(WI_i)_I\ P(FA)_D] + [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \\
& \cdot [1-P(WI_i)_D]
\end{aligned}$$

$$\gamma = [1-P(F)_0]\, P(FA)_0 - [1-P(F)_0]\, P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot P(WI_i)_D$$

$$= [1-P(F)_0]\, P(FA)_0 \cdot [1-P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot P(WI_i)_D]$$

$$\delta = [1-P(F)_0]\, [1-P(FA)_0] + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FI_i)_D$$

Special case when the depot repair cycle is perfect as in Figure 2.6, then

$$P(WI_i)_D = 0$$

$$P(FI_i)_D = 1$$

$$\alpha = 0$$

$$\beta = P(F)_0 - [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D]$$

$$\gamma = [1-P(F)_0]\, P(FA)_0$$

$$\delta = [1-P(F)_0]\, [1-P(FA)_0] + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D$$

2.10 Another Definition for α, β, and γ errors

These new definitions of α, β, and γ errors capitalize on the importance of false removals of RU at any level in affecting the maintainability and availability of the system.

Let

α_ℓ^* = P[unnecessary removal of a good RU from the diagnostic group at level ℓ]

Let β_ℓ^* be the probability of not detecting and/or not isolating a faulty RU at any level ℓ (excluding cases where good RU's are isolated)

β_ℓ^* = P[detecting or isolating no fault|diagnostic group is faulty]

Let γ^* be the correct action of not isolating a good RU after reporting its failure (either at the same level or at a lower level)

γ_ℓ^* = P[correct action of not isolating a good RU after reporting its failure|diagnostic group is good]

2.11 Testability Effectiveness Measures at Any Level of Repair

According to the above definitions of α^*, β^*, γ^* errors and using Figure 2.2, then testability effectiveness measures at any level ℓ (Organizational, Intermediate, or Depot) can be derived as follows:

$\alpha_\ell^* =$ P[false RU report] + P[false RU isolation]

$= [1-P(F)_\ell]\ P(FA)_\ell\ P(WI_i)_\ell + P(F)_\ell\ P(FD)_\ell\ P(FL_i)_\ell$

$\beta_\ell^* =$ Failure to report + Failure to isolate RU

$= P(F)_\ell - [P(F)_\ell\ P(FD)_\ell] + [P(F)_\ell\ P(FD)_\ell - P(F)_\ell\ P(FD)_\ell\ P(FL_i)_\ell - P(F)_\ell$
$P(FD)_\ell\ P(FI_i)_\ell]$

$= P(F)_\ell - P(F)_\ell\ P(FD)_\ell\ P(FL_i)_\ell - P(F)_\ell\ P(FD)_\ell\ P(FI_i)_\ell$

$= P(F)_\ell - P(F)_\ell\ P(FD)_\ell\ [P(FL_i)_\ell + P(FI_i)_\ell]$

$\gamma_\ell^* = CND_\ell$

$= [1-P(F)_\ell]\ P(FA)_\ell - [1-P(F)_\ell]\ P(FA)_\ell\ P(WI_i)_\ell$

$= [1-P(F)_\ell]\ P(FA)_\ell\ [1-P(WI_i)_\ell]$

$\delta_\ell^* =$ P[Successful FD/FI]

$= 1-P(F)_\ell - [1-P(F)_\ell]\ P(FA)_\ell + P(F)_\ell\ P(FD)_\ell\ P(FI_i)_\ell$

$= [1-P(F)_\ell]\ [1-P(FA)_\ell] + P(F)_\ell\ P(FD)_\ell\ P(FI_i)_\ell$

2.12 Testability Effectiveness Measures for the Organizational/Intermediate System

α^*, β^*, γ^* errors for the organizational/intermediate system are derived using the decision tree in Figure 2.4 as follows:

$\gamma_{OI}^* =$ P[removing a good RU at the organizational/intermediate system]

= P[false report (intermediate)] + P[module false isolation]

$= [1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I \cdot P(WI_i)_I + [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I$
$\cdot P(FL_i)_I + [P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I]$

$\beta_{OI}^* =$ P[detecting or isolating no faults | prime equipment is faulty]

= P[failure to report (org.)] + P[failure to report (int.)] + P[failure to isolate LRU] + P[failure to isolate module] + P[no fault isolation] + P[no module isolation]

$$\beta^*_{OI} = [P(F)_0 - P(F)_0 \cdot P(FD)_0] + [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I] + [P(F)_0 \cdot P(FD)_0 - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 - P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0] + [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_o \cdot P(FD)_I \cdot P(FI_i)_I - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FL_i)_I] + [P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 - P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I] + [P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I - P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I]$$

$$= P(F)_0 - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FL_i)_I - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I - P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I$$

γ^*_{OI} = P[correct action of not isolating LRU and/or module after isolating isolating a good LRU]

$$= CND_O + CND_I + RTOK_I$$

$$= [[1-P(F)_0]\ P(FA)_0 - [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0] + [[1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I - [1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I \cdot P(WI_i)_I] + [[1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 - [1-P(F)_0]\ P(WI_i)_0 \cdot P(FA)_0 \cdot P(FA)_I]$$

$$= [1-P(F)_0]\ P(FA)_0 - [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I$$

$$= [1-P(F)_0]\ P(FA)_0\ [1-P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I]$$

δ^*_{OI} = P[successful performance of the diagnostic system in the organizational and intermediate levels as a whole]

= P[isolating the faulty module | prime equipment is faulty]

+ P[reporting no failure | prime equipment is good]

$$= P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I + [1-P(F)_0]\ [1-P(FA)_0]$$

2.13 Testability Effectiveness Measures for the Organizational/Intermediate/Depot System

α^*, β^*, γ^* errors for the organizational/intermediate/depot system are derived using the decision tree in Figure 2.5 as follows:

α^* = P[removing a good RU at the organizational/intermediate/depot]

= P[removing a good unit at the depot level]

$= [1-P(F)_0]\ P(FA)_0 \cdot P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot P(WI_i)_D + P(F)_0 \cdot P(FD)_0$

$\cdot P(FI_I)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FL_i)_D + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I$

$\cdot P(FL_i)_I \cdot P(FA)_D \cdot P(WI_i)_D + P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D$

$\cdot P(WI_i)_D$

β^* = P[detecting or isolating no faults | prime equipment is faulty]

$= P(F)_0 - [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FI_i)_D] - P(F)_0$

$\cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FL_i)_D - P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0$

$\cdot P(FD)_I \cdot P(FL_i)_I \cdot P(FA)_D \cdot P(WI_i)_D - P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I$

$\cdot P(FA)_D \cdot P(WI_i)_D$

γ^* = P[correct action of not isolating LRU, module and/or unit after mistakingly detecting and/or isolating a good LRU or module]

$\gamma^* = \gamma$ as in the previous case in section 2.9

$= [1-P(F)_0]\ P(FA)_0\ [1-P(WI_i)_0 \cdot P(FA)_I \cdot P(WI_i)_I \cdot P(FA)_D \cdot P(WI_i)_D]$

δ^* = P[successful performance of the diagnostic system as a whole]

$= [1-P(F)_0]\ [1-P(FA)_0] + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FI_i)_D$

Special case when the depot repair cycle is perfect as in Figure 2.6.

$P(WI_i)_D = 0$

$P(FI_i)_D = 1$

$P(FL_i)_D = 0$

$\alpha^* = 0$

$\beta^* = P(F)_0 - [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D]$

$\gamma^* = [1-PF)_0]\ P(FA)_0$

$\delta^* = [1-P(F)_0]\ [1-P(FA)_0] + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D$

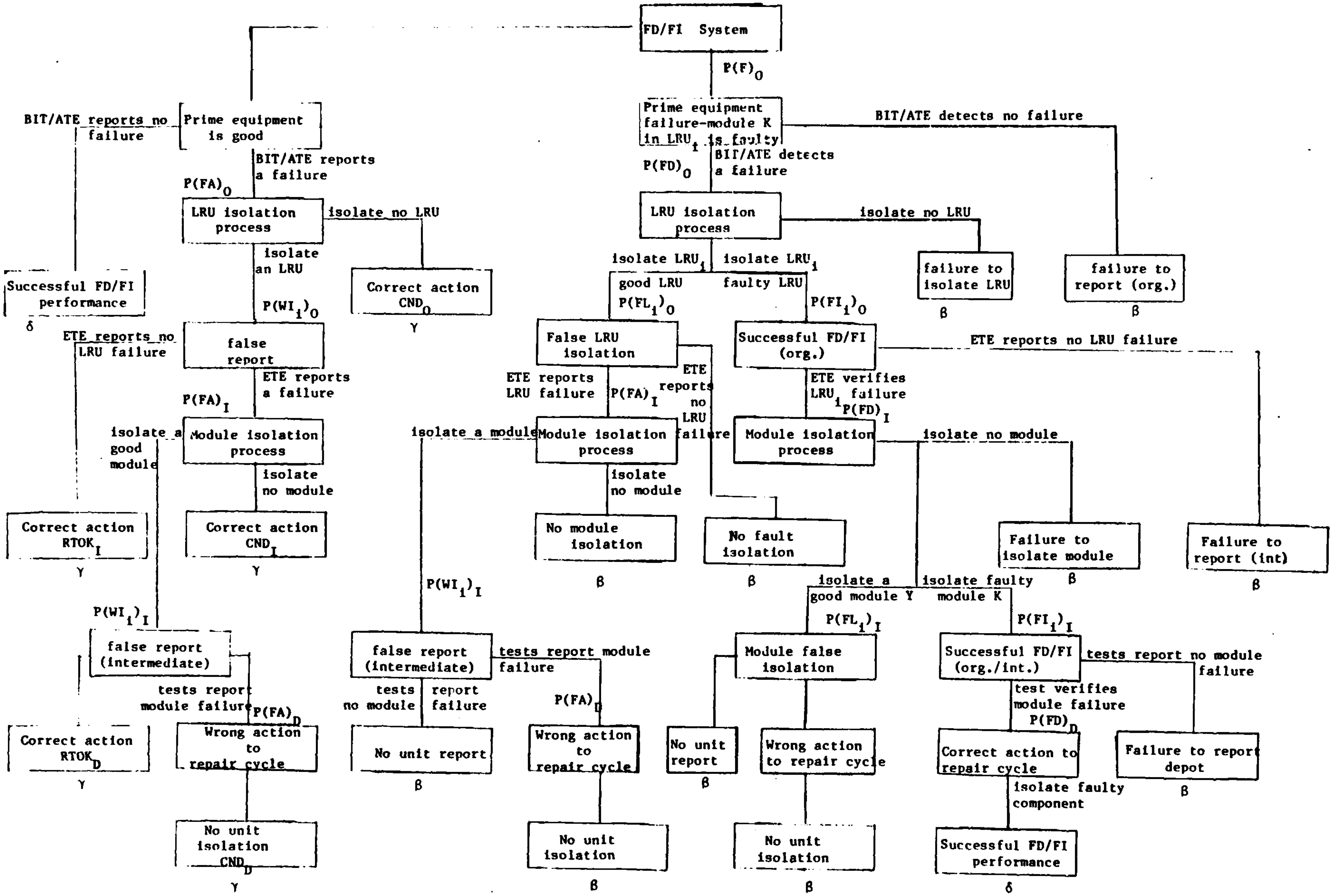

Figure 2.6 Testability Procedures for the Organizational/Intermediate/Depot System with Perfect Depot Repair Cycle.

3. Maintainability, Availability and Reliability

3.1 System Maintainability

System maintainability is defined as a measure of the capability of the diagnostic system to detect, isolate and repair the equipment and return it to its operational status.

Maintainability can also be defined as a characteristic of design and installation which is expressed as the probability that an item will be retained in, or restored to, specified conditions within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources [MIL-STD-721B]. Maintainability can be controlled and improved by increasing the effectiveness of the test equipments.

The primary objective of the maintainability analysis is to translate the so-called requirements into usable maintainability parameters such as mean maintenance down time, allowable maximum maintenance time, mean preventive maintenance time, maintenance manhours per flight hour, turnaround time required for returning the equipment to an operationally ready condition, percentage of equipment which can be down for maintenance and still permit the attainment of the operational requirement, Mean-Time-to-Restore (MTR), the Mean-Time-to-Repair (MTTR) and mean-time-between-maintenance. The most important of the above parameters are MTR and MTTR; therefore, they will be discussed in more detail.

3.1.1 Mean-Time-To-Restore (MTR)

MTR is the mean time interval between shutdown for maintenance and restoration of the system to operating status. This does not include supply time and administrative time. MTR is best used where active single or multiple parallel redundancy exists within the system or subsystem.

The MTR may not include any repair time where the function can be restored by other means. Indeed, with the advent of microcomputers and advanced electronics, restoration may be immediate and automatic since extensive redundancy can be packed into electronic equipments.

The MTR can't be used as a sole maintainability requirement, since the maintainability of the failed item is not completely considered.

3.1.2 Mean-Time-To-Repair (MTTR)

MTTR is defined in MIL-STD-721B as the total corrective maintenance time divided by the total number of corrective maintenance actions during a given period of time. Further, the repair time will consist of those actions required to perform on-line repair of a failed item of equipment. The repair time includes the time to isolate the fault to the LRU level, the time required to remove and replace the item, and the time required to verify that the fault has been corrected. Supply time and administrative time are not included.

The MTTR can also be defined as the elapsed time from start of work on the correction of a malfunction indication to the completion of the maintenance action and verification of the correction.

The Mean-Time-to-Repair, if correctly defined, can provide significant insight into true diagnostic system impact on overall system maintainability and availability. It can also be considered as a measure of the adequacy of the system in meeting real operational requirements.

MTTR may be further broken down into four components:

1) Set-up time
2) Troubleshooting time
3) Remove and replace/repair time
4) Checkout time.

Only the second and fourth components relate to FD/FI capability, while the first and third relate to the design of support equipment and overall system maintainability.

It is important to mention that the MTTR can be used interchangeably with the mean-corrective-maintenance-time ($\overline{M}_{ct}$). Most maintainability parameters and criteria (including the MTTR) are aimed at "primary maintenance". That is, maintenance required to restore a system or equipment to a "specified condition within a given period of time at one level". However, little or no maintainability attention is paid to the problem of "secondary maintenance", that is, the problem of subsequent repair below the LRU level (module and parts).

In addition, the way MTTR is usually defined does not differentiate between the time consumed by the diagnostic system to correctly isolate and repair the faulty unit and the time which is wasted to isolated and repair a good unit, or the time wasted in repairing a unit despite returning it as a bad unit.

Therefore, it is suggested that the MTTR be broken into two major components in order to shed light on the actual maintainability of the system at each level. These components are: the mean-time-for-actual-repair and the mean-time-for-unnecessary-repair.

3.1.3 Maintainability at Different Levels of Repair

In order to evaluate system maintainability at any level of repair, at least two figures should be considered. The first should show, with certain probability, if the fault is correctly detected, how much time it will take the diagnostic system to correctly isolate the fault and replace the faulty replaceable unit. This figure indicates how fast the diagnostic system is, in helping the diagnostic group to recover from a failure and become functional again. This figure can be represented by the Mean-Time-to-Replace at each level. The second figure should show how long, on the average, it will take to repair the isolated replaceable unit and return it as a spare part to the same level it was isolated at. This figure can be decomposed into two different parameters to cover the two cases concerned: returning the replaceable unit as a good spare part or as a bad (faulty) spare part. This figure can be represented by the Mean-Time-to Repair.

From the above discussion, measures of system maintainability at different levels can be redefined to represent the actual real life situation. Furthermore, the new measures will guarantee covering both "primary" and "secondary" maintenance.

3.1.4 System Maintainability at the Organizational Level

The main concern at this level is the capability of the prime equipment to be returned to operational status in a specified period of time (mission time).

The maintainability measures at the organizational level can be defined as follows:

a) **Mean-Time-To-Replace at the Organizational Level (MTR_0)**

If the prime equipment is faulty, then we can assert with probability P_0 that it will take the BIT/ATE time MTR_0 to correctly detect, isolate, replace the faulty LRU, and/or switch to a redundant LRU in order to return the equipment to its normal functional status, where $P_0 = P(FD)_0 \cdot P(FI_1)_0$.

b) **Mean-Time-For-Actual-Repair at the Organizational Level ($MTAR_0$)**

$MTAR_0$ is the elapsed time from start of work on the correction of a faulty LRU, after correct detection, isolation, and removal from equipment, until correctly repairing it (replacing the faulty module with a good one at the intermediate level), and returning this LRU as a good spare part to the organizational level.

Let $M_0(t)$ be the probability that a faulty LRU which was correctly isolated at the organizational level can be repaired in time t (at the intermediate level). When time to repair has the exponential distribution, the probability of repair in time t can be expressed as

$$M_0(t) = 1 - e^{-\mu_I t}$$

where,

MTR_I = mean repair time of LRU's at the intermediate level.

μ_I = repair rate of LRU's at the intermediate levels = $1/MTR_I$

$$M_0(t) = 1 - e^{-t/MTR_I}$$

$$e^{-t/MTR_I} = 1 - M_0(t)$$

$$-t/MTR_I = \ell n\ (1 - M_0(t))$$

$$MTR_I = \frac{-t}{\ell n\ (1 - M_0(t))}$$

If St_{OI} is the shipping time of an LRU between the organizational and intermediate level

$$\therefore MTAR_O = MTR_I + 2St_{OI}$$

c) **Mean-Time-For-Unnecessary-Repair of LRU at the Organizational Level ($MTUR_O$)**

$MTUR_O$ is the elapsed time from start of work on the correction of an LRU (it can be faulty or not) after it has been isolated until returning this LRU as a spare part to the organizational level (either a good LRU is not correctly repaired, and returned as a bad spare part).

d) **Mean-Time-to-Repair LRU ($MTTR_0$)**

$MTTR_0$ is the expected elapsed time from start of work on the correction of LRU failure indication until repairing this LRU and returning it as a spare part at the organizational level. $MTTR_0$ can be computed using its components $MTAR_0$ and $MTUR_0$ as follows:

$$
\begin{aligned}
MTTR_0 = {} & MTAR_0 \cdot [P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot P(FI_i)_I] + \\
& MTUR_0 \cdot (P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot \\
& (1-P(FD)_I) + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot P(FD)_I \cdot (1-P(FI_i)_I) \cdot \\
& + (1-P(F)_0) \cdot P(WI_i)_0]
\end{aligned}
$$

3.1.5 System Maintainability at the Intermediate Level

The main concern at this level is the capability of an LRU to be returned to a serviceable status by the specified test and repair equipment within a specified *period of time.*

The maintainability measures at the intermediate level can be defined as follows:

a) **Mean-Time-to-Replace at the Intermediate Level (MTR_I)**

If the LRU is really faulty, then we can assert with probability P_I, that it will take the external test equipment time MTR_I to correctly verify the failure, isolate and replace the faulty module in order to return the LRU to its normal functional status, where

$$P_I = P(FD)_I \cdot P(FI_i)_I$$

MTR_I = fault detection time + time to isolate faulty module + time to replace faulty module.

b) **Mean-Time-for-Actual-Reapir of Modules ($MTAR_I$)**

$MTAR_I$ is defined as the elapsed time from start of work on the correction of a faulty module (after correct detection and isolation) until correctly repairing it by replacing the faulty component with a good one either at the intermediate or at the depot levels and returning this module as a good spare part to the intermediate level. (Notice that if a faulty module is to be discarded and not repaired, then $MTAR_I = 0$.) Let $M_I(t)$ be the probability that a faulty module which was correctly isolated at the intermediate level can be repaired in time t (at the depot). When the time to repair has the exponential distribution, the probability of repair in time t can be expressed as

$$M_I(t) = 1 - e^{-\mu_D t}$$

MTR_D = mean-time-to-replace modules at the depot

μ_D = repair rate of modules at the depot

$$\mu_D = 1/MTR_D$$

$$M_I(t) = 1 - e^{-t/MTR_D}$$

$$e^{-t/MTR_D} = 1 - M_I(t)$$

$$-t/MTR_D = \ell n\ (1 - M_I(t))$$

$$MTR_D = \frac{-t}{\ell n\ (1 - M_I(t))}$$

If St_{ID} is the shipping time of a module between the intermediate level and the depot, then

$$MTAR_I = MTR_D + 2St_{ID}$$

c) **Mean-Time-for-Unneccessary-Repair of Modules ($MTUR_I$)**

The elapsed time from start of work on the correction of any module (it may be faulty or not) after it has been isolated, until returning this module as a spare part to the intermediate level (either a good module is incorrectly isolated and unnecessarily checked or a faulty module is not correctly repaired then returned as a bad spare part to the intermediate level). This covers the time consumed in the following cases:

- All cases resulting from false module isolation.
- All cases resulting from successfully detecting and isolating the faulty module except the case of successful detection and isolation of the faulty component.
- All cases resulted from isolating a good module.

d) **Mean-Time-to-Repair Modules ($MTTR_I$)**

The Mean-Time-to-Repair Module is the elapsed time from start of work on the correction of module failure indication until repairing this module and returning it as a spare part at the intermediate level. It is a function of $MTAR_I$ and $MTUR_I$, $MTTR_I$ and can be expressed as follows:

$$\begin{aligned} MTTR_I = {} & MTAR_I \cdot [P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot P(FI_i)_D] + MTUR_I \cdot \\ & [P(F)_I \cdot P(FD)_I \cdot P(FL_i)_I + P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I \cdot (1 - P(FD)_D) \\ & + P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I \cdot P(FD)_D \cdot (1 - P(FI_i)_D + (1 - P(F)_I) \cdot \\ & P(WI_i)_I] \end{aligned}$$

3.1.6 System Maintainability at the Depot

The maintainability at the depot can be measured by the capability of the modules to be repaired and returned to a serviceable condition at a specified percentage of unit cost. This can be described by the mean-time-to-replace as well as percent-cost-to-repair.

a) **Mean-Time-to-Replace at the Depot (MTR_D)**

If the module is really faulty, then we can assert with probability P_D, that it will take the test equipment at the depot time MTR_D to correctly verify the failure, isolate and replace the faulty component in order to return the module to its normal operational condition.

$$P_D = P(FD)_D \cdot P(FI_i)_D$$

MTR_D = fault detection time + time to isolate components + time to replace faulty component.

b) **Percent-Cost-to-Repair at the Depot ($PCTR_D$)**

If the module is really faulty, then we can assert with probability P_D that the cost of correctly verifying the failure, isolating, and replacing the faulty module as a percentage of the initial cost of the module is $PCTR_D$.

3.2 Reliability

Reliability is the probability that a system or equipment will give satisfactory performance for a specified period of time when used under stated conditions. When related to a specific mission, reliability may be defined as the probability of a successful mission of given duration under specified use conditions.

The literature on reliability contains other parameters such as Mean-Time-Between-Failure (MTBF), Mean-Time-To-Failure (MTTF), and Mean-Time-To-First-Failure (MTTFF). These three terms can be used interchangeably because of the applicability of the exponential law to the majority of electronic equipments. Under the exponential law these three terms are identical. However, if the failure distribution is not exponential, these terms do not describe the same thing. MTBF is specifically applicable to a population of equipment where we are concerned with the average time between the individual equipment failures. Where we are concerned with one equipment or one system, the measures MTTF and MTTFF are applicable.

The difference between MTTF and MTTFF is the specification of the initial operating conditions and how time is counted. MTTF is a measure of the expected time the system is in an operable state before all the equipments reach a failed state. In arriving at this measure we count time from when the system was initially fully operable until all equipments reach a failed state without repairs made until the system is in a failed state. MTTFF is a measure of the expected time the system is in an operable state allowing individual equipments to be repaired as they fail given that all equipments were initially operable when we began counting time.

3.2.1 Reliability of the Prime Equipment

Beside its main function, the prime equipment, using the BIT/ATE system, has the ability to detect/isolate any malfunction in any LRU if a malfunction exists, or report no malfunction if none exists. Therefore, the reliability of the prime equipment should be affected by the performance of the BIT/ATE system.

Accordingly, reliability of the prime equipment R can be defined as the probability that either the equipment is good and BIT/ATE system reports no failure or the equipment is faulty and the BIT/ATE successfully detects, isolates the faulty LRU and replaces it, providing a down time not exceeding a given time t_c which will not adversely affect the overall mission. Reliability in time t can be expressed as:

$R(t)$ = P[BIT/ATE reports no failure | equipment is good] + P[BIT/ATE correctly detects and ioslates the faulty LRU and replaces it in time t_c | equipment is faulty]

$$R(t) = [1 - P(F)_0] \cdot [1 - P(FA)_0] + P(F)_0 \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot PR(t_c) \tag{3.1}$$

where $P(F)_0$ = probability of equipment failure

$$= 1 - \prod_{i=1}^{N} [e^{-\lambda_{oi} t}]$$

$P(FA)_0$ = probability of false alarm at the organizational level

$P(FD)_0$ = probability of correct detection | equipment is faulty

$P(FI_i)_0$ = probability of correct isolation to i or less LRU's | equipment is faulty

$PR(t_c)$ = prbability that a faulty LRU_j which is correctly isolated can be replaced in time t_c, where t_c is the critical time for replacing the faulty LRU, exceeding which, the mission fails.

Substituting in equation 3.1, then

$$R(t) = [\prod_{i=1}^{N} e^{-\lambda_{oi} t}] \cdot [1 - P(FA)_0] + [1 - \prod_{i=1}^{N} e^{-\lambda_{oi} t}] \cdot P(FD)_0 \cdot P(FI_i)_0 \cdot PR(t_c)$$

It is important to know the distribution of the replacing time of different LRU's in order to find the value of $PR(t_c)$. In any event, if $t_c > t_m$, where t_m is the mission time, or if replacing the faulty LRU will be done automatically after correctly identifying it, through redundancy for example, then $PR(t_c) = 1$.

3.2.2 Mean-Time-Between-Failures (MTBF)

Mean life or mean-time-between-failurs (MTBF) is the total operating time of the prime equipment divided by the total number of failures, where

total number of failures = number of actual failures (detected) + number of false alarms.

$$\lambda = \text{equipment failure rate} = \frac{\text{number of actual failures}}{\text{operating time}}$$

$$\text{number of false alarms} = P(FA)_0 \cdot \frac{NF}{P(F)_0} \cdot (1 - P(F)_0)$$

NF = number of actual failures

$$MTBF = \frac{\text{operating time}}{\text{number of actual failures + number of false alarms}}$$

$$\frac{1}{MTBF} = \lambda + \frac{P(FA)_0 \cdot \lambda (1 - P(F)_0)}{P(F)_0}$$

$$MTBF = \frac{P(F)_0}{\lambda [P(F)_0 + P(FA)_0 \cdot (1 - P(F)_0)]}$$

Notice that in case of ignoring the false alarm (as in most definitions of (MTBF), $MTBF = \frac{1}{\lambda}$

3.3 System Availability

System availability is the probability that a system or equipments when used under stated conditions in an ideal support environment (i.e., available tools, spares, manpower, etc.), will operate satisfactorily at any point in time. It excludes preventive maintenance actions, logistics supply time, and administrative downtime.

Availability is a complex function of the LRU's failure rate, operating time (reliability), and down time (maintainability/supportability). In general, availability can be expressed as

$$A = \frac{MTBF}{MTBF + MTTR}$$

where

$$MTBF = \frac{P(F)_0}{\lambda[P(F)_0 + P(FA)_0 \cdot (1 - P(F)_0)]}$$

4. Cost of Testability Performance

In this section, the costs involved in testability performance at all levels of repair are analyzed, then the expected costs associated with the errors of the diagnostic system are developed, modeled, and used to shed the light on the actual system effectiveness. These costs are used to compute a very realistic life cycle cost for the equipment/system that takes care of the actual performance of the equipment and the resulting consequences from the performance of the diagnostic system (actual failure, false alarm, CND, RTOK, false isolation, etc.)

4.1 Cost Elements at Different Levels

In this section all cost elements at all different levels are presented. In addition, the following parameters are also considered.

a) **Spare Parts Availability (Asp)**

Spare parts availability is a measure of how available the spare parts are when needed. It is the probability that there is a spare part available when one is needed at the organizational level.

b) **Mission Survival Factor (V)**

Mission survival factor is a measure of how vital the failure of any LRU is to the success of the mission and can be represented as:

V = Prob. [the mission can be accomplished with any faulty LRU]

$$V = \sum_{i=1}^{N} P[\text{mission can be accomplished} \mid LRU_i \text{ is faulty}] \cdot P[LRU_i \text{ is faulty}]$$

c) **Mission Abortion Factor P(MA)**

Mission abortion factor is a measure of the possibility of aborting the mission as a result of the confusion caused by CND_0 and can be represented as:

$P(MA) = \text{Prob. } [\text{mission abortion} \mid CND_0]$

d) **Discard Factor D_I)**

Discard factor is the probability that any module will be discarded at the intermediate level instead of being introduced to the depot.

4.1.1 Costs of BIT/ATE Implementation (CI_0)

The costs associated with the BIT/ATE implementation include:

1. Acquisition Costs (CA_0)
   a. the cost of BIT/ATE hardware
   b. *the cost of BIT/ATE software*
2. Initial Logistics Support Costs (CL_0)
   a. the initial cost of training personnel to maintain the BIT/ATE system
   b. any one time cost associated with the introduction of the BIT/ATE system into the maintenance concept

Acquisition and initial logistics support costs are one time costs associated with the implementation of the BIT/ATE system. Hence, CI_0 is a one time implementation cost for the BIT/ATE system, where

$CI_0 = CA_0 + CL_0$

4.1.2 BIT/ATE Execution/Isolation Cost (CLI)

a. software maintenance - the expenditure resulting from inherent software error corrections and future change requirements.

b. technical data maintenance - the cost of updating and revising technical publications.

c. attrition training - the cost of training new maintenance personnel.

d. *maintenance* labor - the cost of labor to maintain the BIT/ATE system.

e. maintenance material - the cost of material to repair the BIT/ATE system when it malfunctions.

A study by Bogard et al. (1980) investigates Operations and Support costs, and finds that the maintenance material and labor costs for a BIT/ATE system are negligible. Furthermore, software maintenance costs, which usually account for the majority of the BIT/ATE system Operations and Support costs, are strongly correlated with the number of hours that the BIT/ATE system is in operation. So the Operations and Support cost for the BIT/ATE system is dependent on the frequency with which the system is executed. This cost is incurred each time that the BIT/ATE isolation process is executed, and is called the LRU isolation cost.

LRU isolation cost is the average cost of isolating an LRU by BIT/ATE assuming that the BIT/ATE system indicates a failure. This cost is a function of the isolation procedure and cost of different tests which can be used by BIT/ATE.

$$CLI = \sum_{i=1}^{N} CLI_i \cdot P(f_i)_0$$

where

CLI_i = cost of isolating LRU_i

$P(f_i)_0$ = probability of LRU_i failure.

4.1.3 LRU Removal and Replacement Costs (CLR)

Removing an LRU from a digital system at the organizational level, and replacing it with a spare, involves disconnecting the LRU, removing it, inserting a spare in the system, and connecting the spare. Some fixed costs may be included in the removal cost, while the time to remove the LRU is dependent on the number of modules it contains.

The time to disconnect and reconnect the LRU is a function of the number of connections that must be severed. Any connection between a module in LRU_j and a module not within LRU_j must be disconnected in order to remove the LRU. These are the external connections of the LRU, and the number of external connections is denoted E_j.

The cost of the time it takes to remove and replace LRU_j, CLR_j, generally depends on the labor rate and the crew size.

Caponecchi (1971) develops an empirical relationship for the time to remove and replace an LRU from the system. It can be modified in this problem to express the cost of removing and replacing LRU_j, which is:

$$CLR_j = \varepsilon_1 + \varepsilon_2 M_j + \varepsilon_3 e^{\varepsilon_4 E_j} + CL_j$$

where ε_1 is a fixed cost, ε_2 is a cost associated with each module of the LRU, ε_3 is a cost modifying the exponential relationship of the number of connections, ε_4 is a constant modifying the number of connections, and CL_j is cost of LRU_j.

The expected cost to remove an LRU from the equipment/system, CLR, is computed as

$$CLR = \sum_{i=1}^{N} CLR_i \cdot P(f_i)_0$$

where $P(f_i)_0$ is the probability that LRU_i is the faulty LRU.

4.1.4 Shipping Cost from the Organizational Level to the Intermediate Level Per LRU (CS_{OI})

$$CS_{OI} = (WL) \cdot (CPP_{OI})$$

where

WL = average weight of LRU or group of LRU's

$$WL = \sum_{i=1}^{N} (WL_i) \cdot n_0/N$$

n_0 = number of LRU's in the isolated group of LRU's

CPP_{OI} = cost per pound of transportation and packaging between the organizational and intermediate levels

WL_i = weight of LRU_i

4.1.5 Cost of Mission Abortion (CMA)

Cost of mission abortion is all the costs resulting from aborting the mission and not accomplishing the mission goals with all the resulting consequences.

4.1.6 Cost of Mission Failure (CMF)

Cost of mission failure includes costs of all equipments and personnel involved in the mission plus cost of the pride and the national impacts from the mission failure.

4.1.7 Average LRU Cost (CL)

Average LRU cost, which is included in the cost of removal and replacement (CLR), can be computed as follows:

$$CL = \left(\sum_{i=1}^{N} CL_i\right)/N$$

where CL_i = cost of LRU_i

4.1.8 Expected Cost Resulting from Having a Faulty Spare Part at the Organizational Level ($\overline{CF}_0$)

The expected cost resulting from having a faulty LRU coming from the intermediate level as a spare part at the organizational level can be computed using the decision tree of Figure 2.2, including all costs resulting from replacing any LRU (faulty or good) by a faulty LRU with costs of all consequences.

$$\begin{aligned}\overline{CF}_0 = {} & [1 - P(F)_0]\cdot P(FA)_0\cdot P(WI_i)_0\cdot (1 - V)\ (Asp)\ [CLI + CLR + CMF] \\ & + [1 - P(F)_0]\cdot P(FA)_0\cdot P(WI_i)_0\cdot V\cdot (Asp)\ [CLI + CLR] + P(F)_0\cdot P(FD)_0 \\ & \cdot P(FI_i)_0\cdot (1 - V)\ (Asp)\ [CLI + CLR + CMF] + P(F)_0\cdot P(FD)_0\cdot P(FI_i)_0 \\ & \cdot V\ (Asp)\ [CLI + CLR]\end{aligned}$$

4.1.9 Costs of External Tests Implementation (CI_I)

At the intermediate level, costs associated with external test equipment include:

1. Acquisition Costs - the cost of procuring the external test equipment.
2. Initial Logistics Support Costs
   a. the initial cost of training operators and maintenance personnel.
   b. any one time cost associated with introducing the external test equipment into the maintenance cycle.

The costs of external tests implementation is a one time cost incurred every time an LRU (faulty or good) is introduced to the intermediate level.

4.1.10 Operations and Support Costs of External Tests

a. software maintenance - if the equipment is semiautomatic and software based.

b. technical data maintenance - the cost of updating and revising technical publications such as operator handbooks and maintenance manuals.

c. attrition training - the cost of training new operators and maintenance personnel.

d. maintenance material - the cost of material to repair the test equipment when it fails.

e. maintenance labor - the cost of labor to maintain the test equipment.

f. operations labor - the cost of employing the test.

Bogard et al. (1980) find that for external test equipment, operations labor and software maintenance, when applicable, tend to be the dominant costs.

Cost of testing, screening and detection of failure in an LRU at the intermediate level, CMD, can be computed as

$$CMD = CI_I + n_0(ct)\,(SR)\,(TMD)\,(NMD)/(UR)\,(H)$$

where

TMD = average time required for testing, screening and detection of failure in an LRU at the intermediate level

NMD = Number of technicians required to test, screen and detect a failure in an LRU at the intermediate level

ct = annual cost to provide a trained technician for maintenance (annual labor cost) at the intermediate level

SR = shop support ratio (total personnel at the intermediate level divided by the number of maintenance and operating personnel)

UR = manpower utilization rate at the intermediate level

H = number of working hours per year in the intermediate level

The average time required for diagnosis of the LRU failure at the intermediate level, TMI, will be a direct function of LRU size. On the average, one-half of the modules in the LRU will need to be examined in order to find the faulty one. TMI is of the form

$$TMI = 1/2(TM)\ (M)n_0$$

where TM = average time to test one module for malfunction

$$TM = \left(\sum_{i=1}^{N}\ \sum_{j=1}^{M_i} TM_{ij}\right) / \sum_{i=1}^{N} M_i\ ,\ \text{and}$$

TM_{ij} = time to test module j of LRU_i

M = average number of modules in any LRU

$$M = \left(\sum_{i=1}^{N} M_i\right)/N$$

and cost of module isolation is

$$CMI = (ct)\ (SR)\ (TMI)\ (NMI)/(UR)\ (H)$$

where

NMI = number of technicians required for isolating a failed module in the intermediate level.

4.1.11 Average Module Cost (CM)

Average module cost can be computed as follows:

$$CM = \left(\sum_{i=1}^{N}\ \sum_{j=1}^{M_i} CM_{ij}\right) / \sum_{i=1}^{N} M_i$$

where CM_{ij} = cost of module j in LRU_i

4.1.12 Module Removal and Replacement Cost (CMR)

Cost of removing and replacing modules including cost of modules, at the intermediate level can be computed as follows:

$$CMR = n_I \cdot (CM) + (ct)\,(SR)\,(TMR)\,(NMR)/(UR)\,(H)$$

where TMR = average time to remove and replace the faulty module and check out an LRU at the intermediate level

$$TMR = \left(\sum_{i=1}^{N} \sum_{j=1}^{M_i} TMR_{ij}\right) / \sum_{i=1}^{N} M_i$$

TMR_{ij} = time to remove and replace module j of LRU_i

NMR = number of technicians required to remove and replace a failed module at the intermediate level

n_I = number of modules in the isolated group of modules

4.1.13 Shipping Cost per Module Between the Intermediate Level and Depot Level (CS_{ID})

Shipping cost per module between the intermediate level and depot level includes also packaging and handling costs and can be expressed as:

$$CS_{ID} = (WM)(CPP_{ID})$$

where WM = average module weight

$$WM = n_I \left(\sum_{i=1}^{N} \sum_{j=1}^{M_i} WM_{ij}\right) / \sum_{i=1}^{N} M_i$$

WM_{ij} = weight of module j of LRU_i

CPP_{ID} = cost per pound of transportation and packaging between the intermediate and depot levels.

4.1.14 Cost of Discarding Any Module (CMT)

Cost of discarding or throwing away any module includes all the costs incurred to get rid of the module or the scrap value if it can be sold (negative cost).

4.1.15 Expected Cost Resulting from Having a Faulty Spare Part at the Intermediate Level ($\overline{CF}_I$)

The expected cost resulting from having a faulty module (coming from the depot) as a spare part at the intermediate level can be computed using the decision tree of Figure 2.2, including all costs resulting from replacing any module (faulty or good) by a faulty module with costs of all consequences.

$$\overline{CF}_I = [1 - P(F)_I] \cdot P(FA)_I \cdot P(WI_i)_I \cdot [CMD + CMI + CMR + CS_{OI} + \overline{CF}_O] + P(F)_I \cdot P(FD)_I \cdot P(FI_i)_I \cdot [CMD + CMI + CMR + CS_{OI} + \overline{CF}_O] \ .$$

4.1.16 Cost of Testing Component/Part (CPR)

Cost of testing, screening and detection of failure in a module at the depot is

$$CPD = \eta_I \, (HDC)(TPD) \cdot (NPD)$$

where HDC = hourly depot time repair cost

TPD = time required for testing, screening and detection of a failure in a module in the depot

NPD = number of repair persons required to test, screen and detect a failure in a module in the depot.

4.1.17 Cost of Isolating Component/Part (CPI)

Cost of isolating components or parts at the depot is

$$CPI = \eta_I (HDC)(TPI)(NPI)$$

where TPI = average time required for diagnosis of the module failure in the depot

NPI = number of repair persons required for isolating a failed module in the depot.

4.1.18 Average Cost of Component/Part (CP)

Average cost of component/part can be computed as follows:

$$CP = \left(\sum_{i=1}^{N} \sum_{j=1}^{M_i} \sum_{k=1}^{U_{ji}} CP_{ijk} \right) / \sum_{i=1}^{N} \sum_{j=1}^{M_i} U_{ji}$$

where CP_{ijk} = cost of component/part k in module j of LRU_i

4.1.19 Cost of Removing and Replacing Component/Part (CPR)

Cost of removing and replacing component/part in the depot including cost of component/part is:

$$CPR = (HDC)(TPR)\ (NPR) + (CP)\ \eta_D$$

η_D = number of the components/parts in the isolated group of components/parts

TPR = average time to remove and replace the faulty component and check out the module

$$= \left(\sum_{i=1}^{N} \sum_{j=1}^{M_i} \sum_{k=1}^{U_{ji}} TPR_{ijk} \right) / \sum_{i=1}^{N} \sum_{j=1}^{M_i} U_{ji}$$

TPR_{ijk} = time to remove and replace component k in the module j of LRU_i

U_{ji} = number of components in module j of LRU_i

NPR = number of repair persons required to remove and replace a failed component

4.1.20 Expected Cost of Introducing a Good Module to the Depot Level ($\overline{C}_D$)

Expected cost of introducing a good module to the depot can be computed considering all decisions emanated from the node concerning good RU (component) in Figure 2.2 as well as the associated costs.

$$\overline{C}_D = [1 - P(FA)_D][(CPD + CS_{ID}] + P(FA)_D\ [1 - P(WI_i)_D][CPD + CPI + CS_{ID}]$$
$$+ P(FA)_D \cdot P(WI_i)_D[CPD + CPI + CPR + CPT + CS_{ID}]$$

4.1.21 Expected Cost of Introducing a Good LRU to the Intermediate Level ($\overline{C}_I$)

Expected cost of introducing a good LRU to the intermediate level can be computed considering all decisions emanated from the node concerning good RU (module) in Figure 2.2 as well as the associated costs.

$$\overline{C}_I = [1 - P(FA)_I] \cdot [CMD + CS_{OI}] + P(FA)_I\ [1 - P(WI_i)_I][CMD + CMI + CS_{OI}]$$
$$+ P(FA)_I \cdot P(WI_i)_I \cdot [CMD + CMI + D_I \cdot (CMT + (1 - D_I) \cdot \overline{C}_D]$$

4.2 Costs Associated with Testability at the Depot

In this section, costs associated with testability at the depot are presented. This includes costs associated with α, β, γ errors and those associated with a successful performance of the diagnostic system. Then these costs are used to develop a new cost-measure of effectiveness at the depot.

4.2.1 Expected Cost of α Error ($C\alpha_D$)

Costs associated with α error are costs of testing, isolation, removal, and replacement of component/part plus cost of throwing away a good component/part, and returning a good module to the intermediate level as a good spare part.

$$C\alpha_D = [1-P(F)_D]\cdot P(FA)_D \cdot P(WI_i)_D \; [CPD + CPI + CPR + CPT + CS_{ID}]$$

4.2.2 Expected Cost of β Error ($C\beta_D$)

Costs associated with β error are presented in Figure 4.1,

$$\begin{aligned} C\beta_D = {} & P(F)_D \; [1-P(FD)_D][CPD + CS_{ID} + \overline{CF}_I] \\ & + P(F)_D \cdot P(FD)_D \; [1-P(FI_i)_D - P(FL_i)_D][CPD + CPI + CS_{ID} + \overline{CF}_I] \\ & + P(F)_D \cdot P(FD)_D \cdot P(FL)_i)_D \; [CPD + CPI + CPR + CPT + CS_{ID} + \overline{CF}_I] \end{aligned}$$

4.2.3 Expected Cost of γ Error ($C\gamma_D$)

Costs associated with γ error are these of unnecessary testing, and isolation of components plus cost of shipping the good module back to the intermediate level,

$$C\gamma_D = [1-P(F)_D]\cdot P(FA)_D \cdot [1-P(WI_i)_D][CPD + CPI + CS_{ID}]$$

4.2.4 Cost-Measure of Effectiveness at the Depot

Using the costs associated with α, β, and γ errors at the depot level and the probability of their occurances, a new cost-measure of effectiveness can be derived by computing the expected cost of errors of the diagnostic system $\overline{C}_D$,

$$\overline{C}_D = C\alpha_D + C\beta_D + C\gamma_D$$

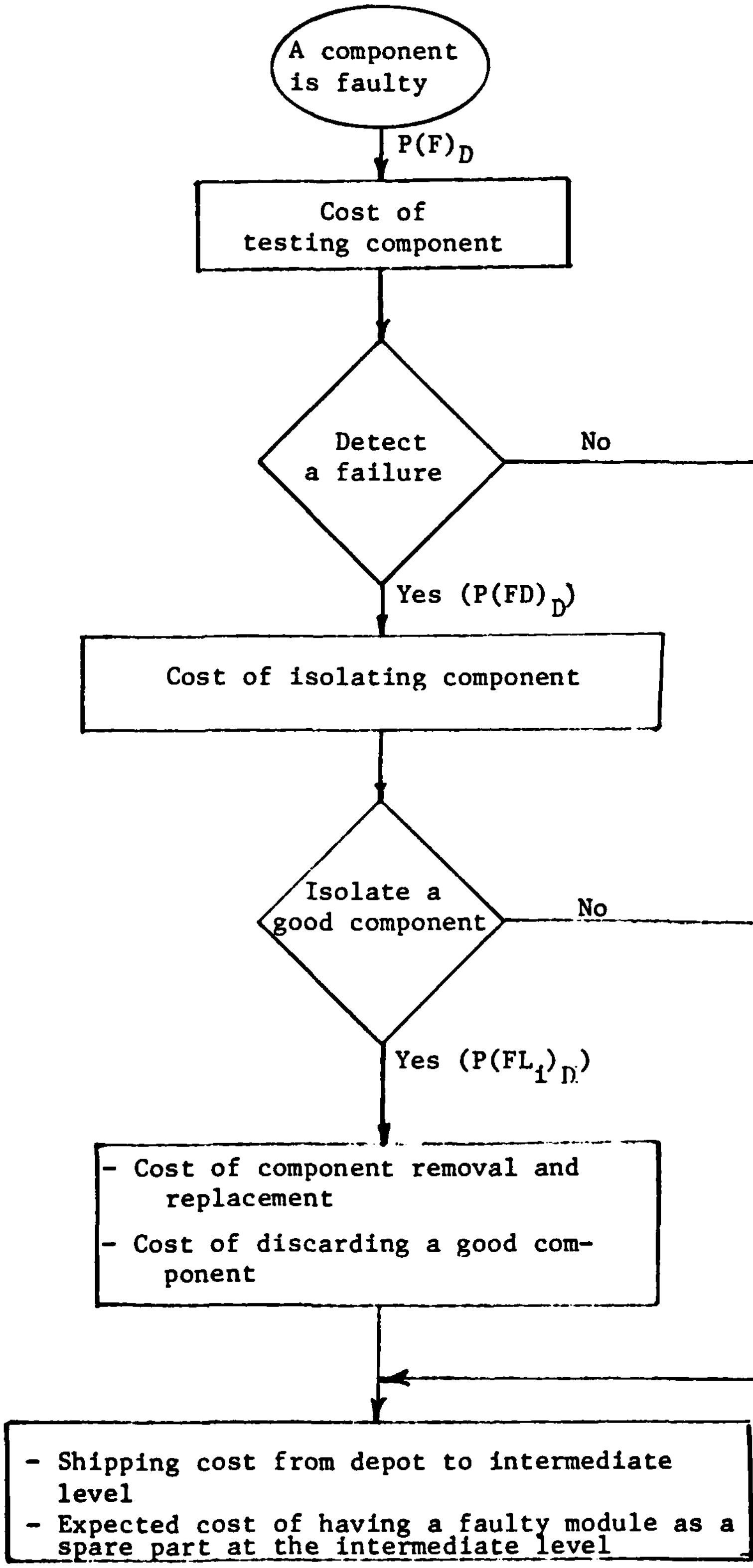

Figure 4.1 Costs Associated with β Error at the Depot

4.2.5 Expected Costs of a Successful Performance of the Diagnostic System at the Depot ($C\delta_D$)

The costs associated with a successful performance of the diagnostic system include costs involved when a faulty module is introduced to the depot as presented in Figure 4.2, and those involved when a good module is introduced to the depot.

$$C\delta_D = P(F)_D \cdot P(FD)_D \cdot P(FI_i)_D \, [CPD + CPI + CPR + CPT + CS_{OI}] +$$
$$\cdot [1 - P(F)_D] \cdot [1 - P(FA)_D] \cdot [CPD + CS_{ID}]$$

4.2.6 Expected Cost of Introducing a Faulty Module to the Depot ($\overline{CG}_D$)

The costs involved are the costs associated with both β error and a successful performance of the diagnostic system when a faulty module is introduced to the depot.

$$\overline{CG}_D = C\beta_D + C\delta_D - [1 - P(F)_D] \, [1 - P(FA)_D] \, [CPD + CS_{ID}]$$

4.3 Costs Associated with Testability at the Intermediate Level

In this section, costs associated with testability at the intermediate level are presented. This includes costs associated with α, β, γ errors, and successful performance of the diagnostic system. Then these costs are used to develop a new cost-measure of effectiveness at the intermediate level.

4.3.1 Expected Cost of α Error ($C\alpha_I$)

Costs associated with α error are presented in Figure 4.3,

$$C\alpha_I = [1-P(F)_I] \cdot P(FA)_I \cdot P(WI_i) \, [CMD + CMI + CMR + D_I \, (CMT) +$$
$$(1-D_I) \, (CS_{ID} + \overline{C}_D)]$$

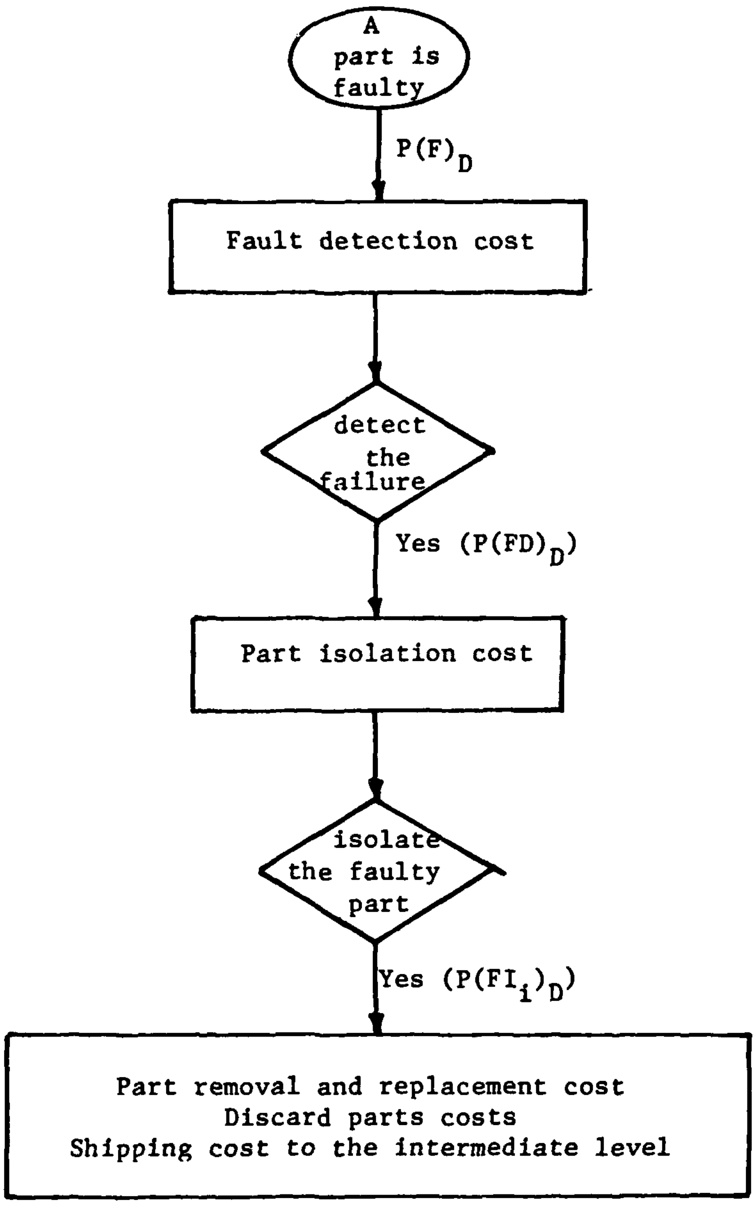

Figure 4.2 Costs Associated with Successful Performance at the Depot

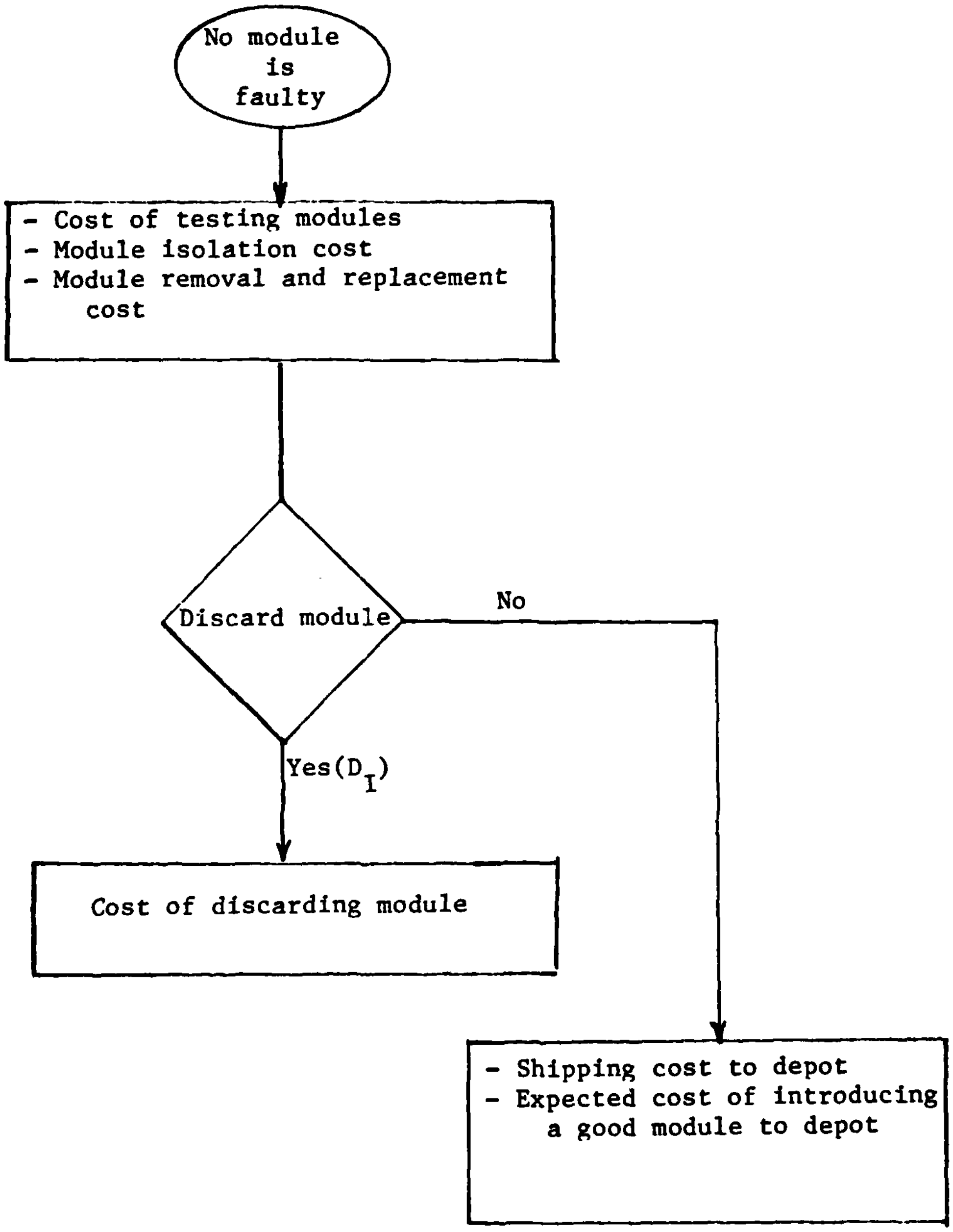

Figure 4.3 Costs Associated With α Error at the Intermediate Level

4.3.2 Expected Cost of β Error ($C\beta_I$)

Costs associated with β error are presented in Figure 4.4,

$$\begin{aligned} C\beta_I = {} & P(F)_I \cdot [1-P(FD)_I] \cdot (CMD + CS_{OI} + \overline{CF}_O) \\ & + P(F)_I \cdot P(FD)_I\ [1-P(FL_i)_I - P(FI_i)_I]\ (CMD + CMI + CS_{OI} + \overline{CF}_O) \\ & + P(F)_I \cdot P(FD)_I \cdot P(FL_i)_I\ (CMD + CMI + CMR + D_I\ (CMT) + CS_{OI} \\ & + \overline{CF}_O + (1-D_I)(CS_{ID} + \overline{C}_D)) \end{aligned}$$

4.3.3 Expected Cost of γ Error ($C\gamma_I$)

Costs associated with γ error are these of unnecessary module testing, isolation and shipping the good LRU back to the organizational level.

$$C\gamma_I = [1-P(F)_I] \cdot P(FA)_I \cdot [1-P(WI_i)_D][CMD + CMI + CS_{OI}]$$

4.3.4 Cost-Measure of Effectiveness at the Intermediate Level

Using the costs associated with α, β, and γ errors at the intermediate level and the probability of their occurences, a new cost-measure of effectiveness can be derived by computing the expected cost of errors of the diagnostic system ($\overline{C}_I$), where

$$\overline{C}_I = C\alpha_I + C\beta_I + C\gamma_I$$

4.3.5 Expected Cost of a Successful Performance of the External Test Equipment at the Intermediate Level ($C\delta_I$)

The costs associated with a successful performance of the external test equipments are those involved when a faulty LRU is introduced to the intermediate level as presented in Figure 4.5 and those involved when a good LRU is introduced to the intermediate level.

$$\begin{aligned} C\delta_I = {} & P(F)_I\ P(FD)_I\ P(FI_i)_I\ [CMD + CMI + CMR + D_I(CMT)] + (1 - D_I) \cdot \\ & (CS_{ID} + \overline{CG}_D)] + [1 - P(F)_I]\ [1 - P(FA)_I]\ [CMD + CS_{OI}] \end{aligned}$$

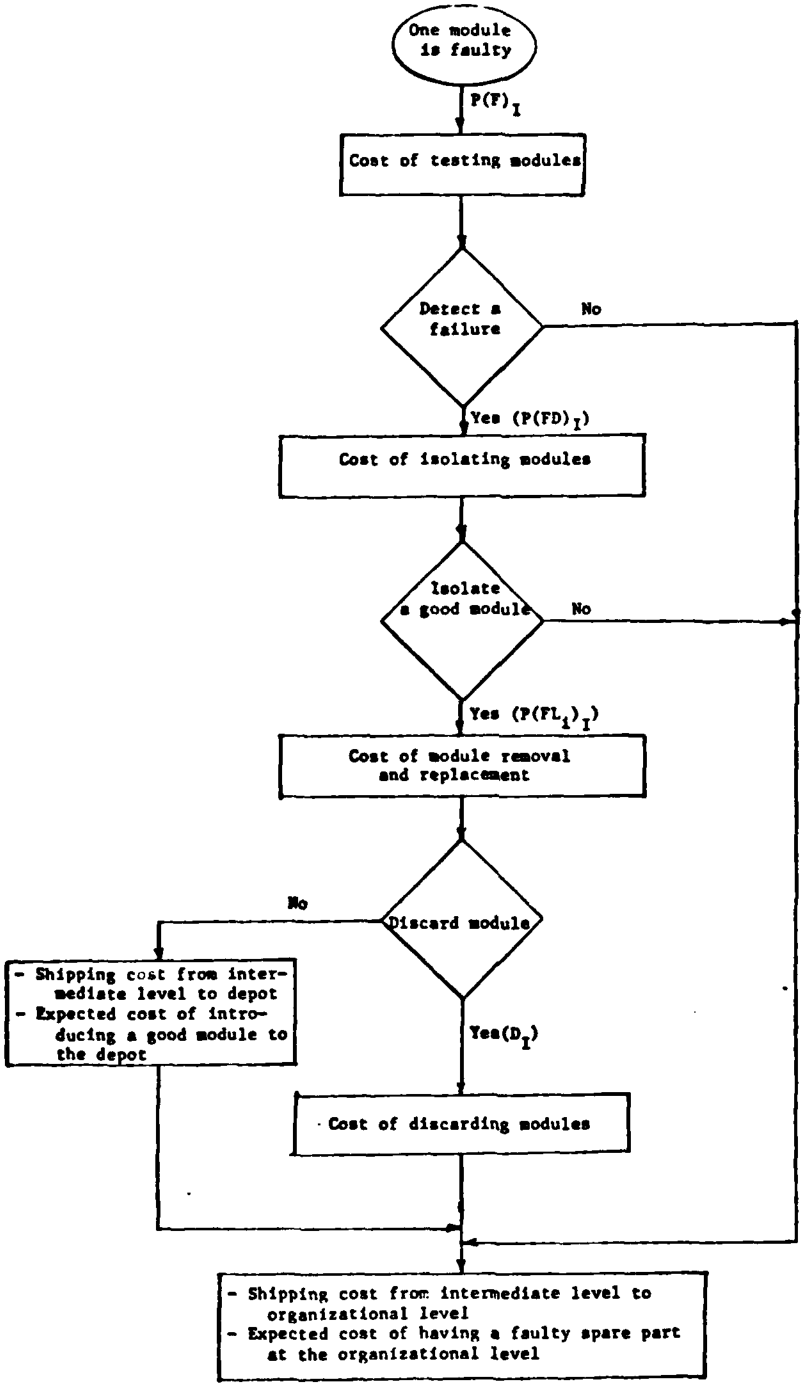

Figure 4.4 Costs Associated with β Error at the Intermediate Level

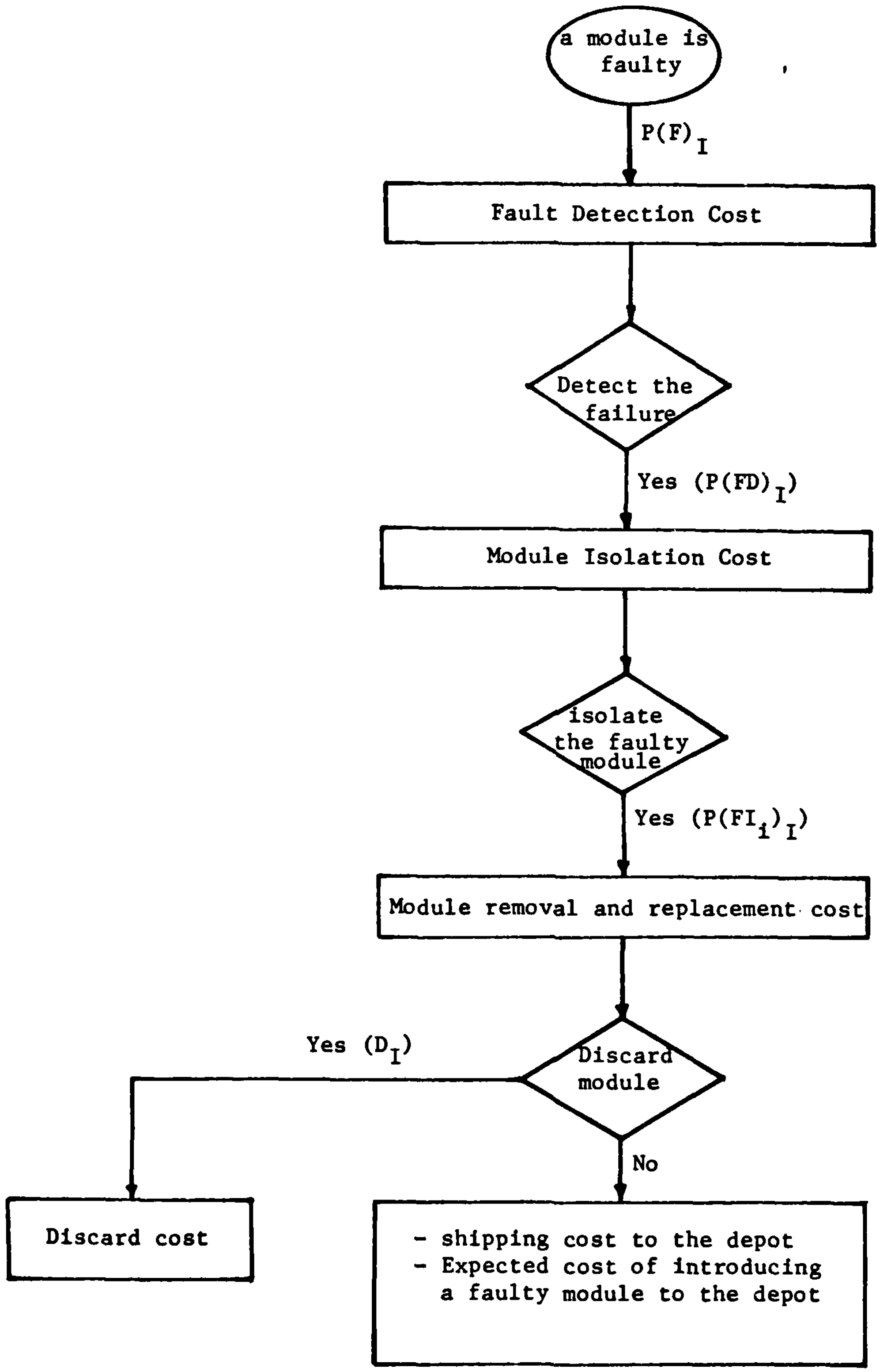

Figure 4.5 Costs Associated with Successful Performance at the Intermediate Level

4.3.6 Expected Cost of Introducing a Faulty Module to the Intermediate Level ($\overline{CG}_I$)

The costs involved are the costs associated with both β error and a successful performance of the external test equipment at the intermediate level.

$$\overline{CG}_I = C\beta_I + C\delta_I - [1 - P(F)_I]\,[1 - P(FA)_I]\,[CMD + CS_{OI}]$$

4.4 Costs Associated with Testability at the Organizational Level

In this section, costs associated with testability at the organizational level are presented. This includes costs associated with α, β, γ errors, and a successful performance of the BIT/ATE system. Then these costs are used to develop a new cost-measure of effectiveness at the intermediate level as well as an expected life cycle cost of the equipment/system.

4.4.1 Expected Cost of α Error ($C\alpha_0$)

Costs associated with α error are presented in Figure 4.6,

$$C\alpha_0 = [1-P(F)_0] \cdot P(FA)_0 \cdot P(WI_i)_0 \cdot \{[Asp + V\,(1-Asp][CLI + CLR + CS_{OI} + \overline{C}_I] + (1 - Asp)(1 - V)[CMA + CLI + CLR + CS_{OI} + \overline{C}_I]\}$$

4.4.2 Expected Cost of β Error ($C\beta_0$)

Costs associated with β error are presented in Figure 4.7.

$$C\beta_0 = P(F)_0 \cdot [1 - P(FD)_0]\,(1 - V)\,(CMF) + P(F)_0 \cdot P(FD)_0 \cdot [1 - P(FI_i)_0 - P(FL_i)_0]\,[CLI + (1 - V)(CMF)] + P(F)_0 \cdot P(FD)_0 \cdot P(FL_i)_0 \cdot \{(1 - V)(CMF) + V(1 - Asp)(CMA + CLI + CLR + CS_{OI} + \overline{C}_I) + V(Asp)\,[CLI + CLR + CS_{OI} + \overline{C}_I]\}$$

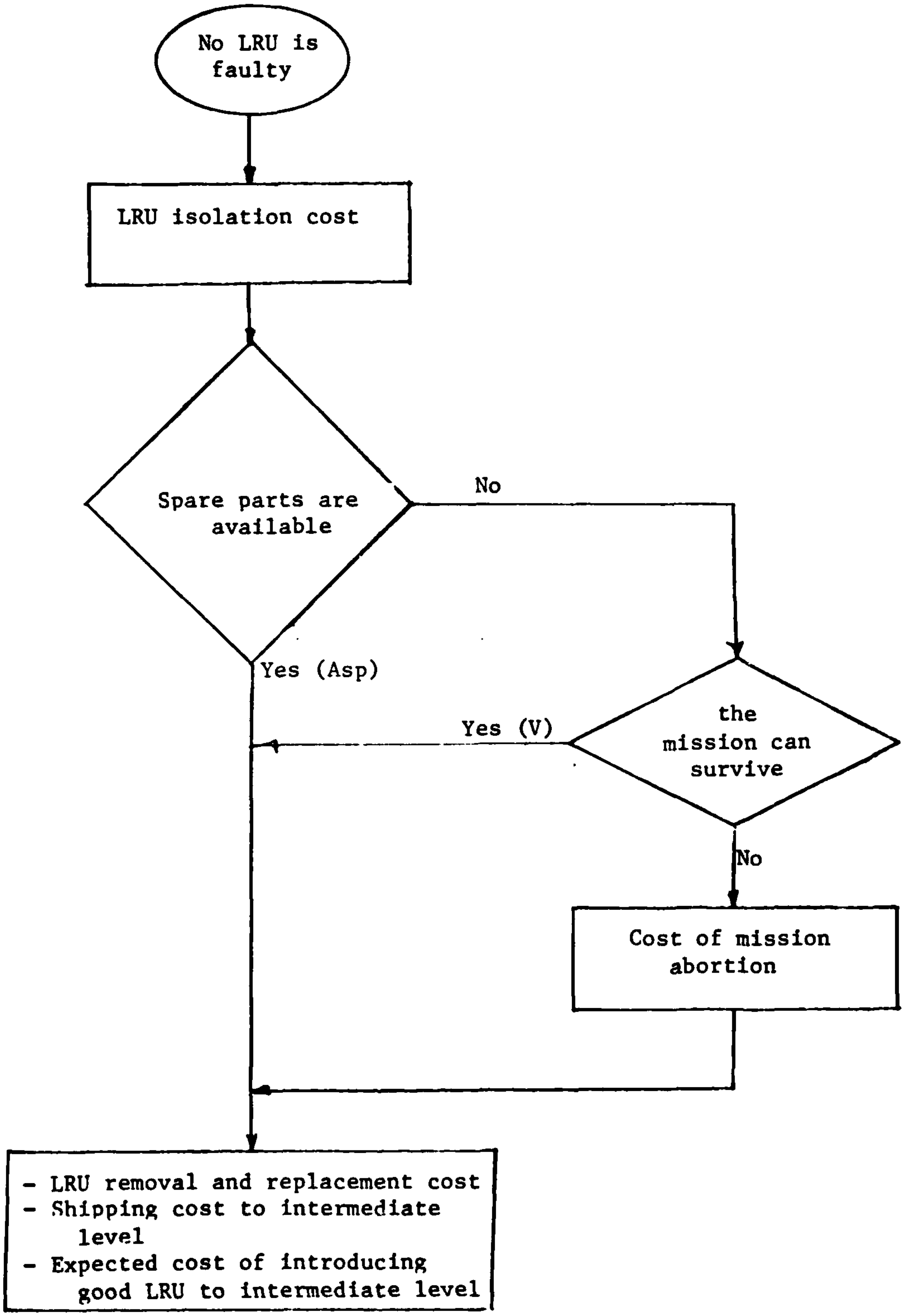

Figure 4.6 Costs Associated With α Error at the Organizational Level

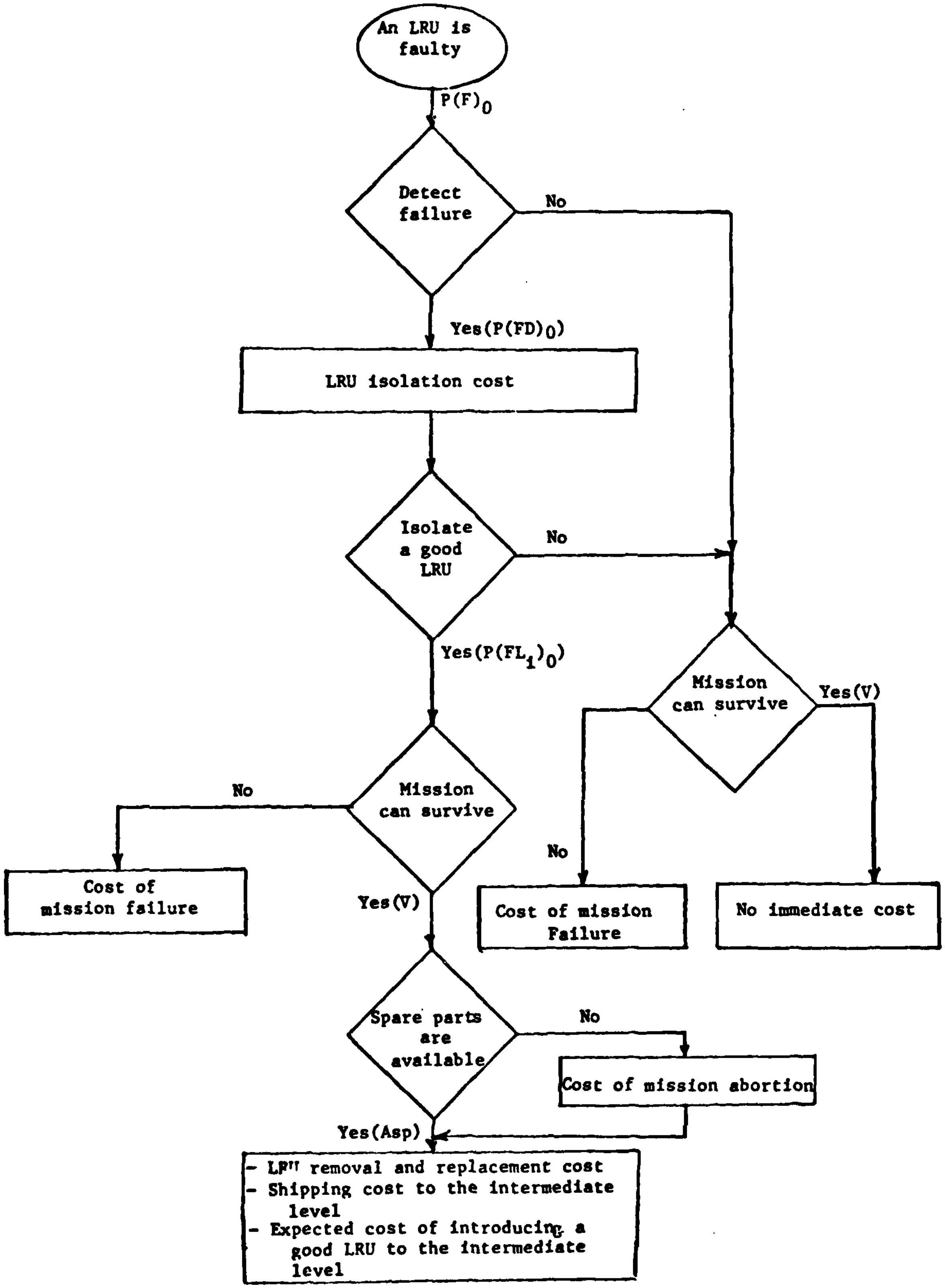

Figure 4.7 Costs Associated with β Er... at the Organizational Leve...

4.4.3 Expected Cost of γ Error ($C\gamma_0$)

Costs associated with γ error are only the costs of the unnecessary LRU isolation cost and costs of interruptions and confusions which might lead to mission abortion. Hence,

$$C\gamma_0 = [1 - P(F)_0]\cdot P(FA)_0\cdot [1 - P(WI_i)_0]\cdot [(CMA)\cdot P(MA) + CLI]$$

4.4.4 Cost-Measure of Effectiveness at the Organizational Level

Using the costs associated with α, β, and γ errors at the organizational level and the probability of their occurances, a new cost-measure of effectiveness can be derived by computing the expected cost of the errors of the diagnostic system ($\overline{C}_0$), where

$$\overline{C}_0 = C\alpha_0 + C\beta_0 + C\gamma_0$$

This measure represents the actual burden of the imperfection of the diagnostic system, including both probabilities of errors and costs resulted from these errors.

4.4.5 Expected Cost of a Successful Performance of the BIT/ATE System ($C\delta_0$)

The costs associated with a successful performance of the BIT/ATE system are those of LRU isolation costs, shipping costs to the intermediate level, and the expected cost of introducing a faulty LRU to the intermediate level as shown in Figure 4.8.

$$C\delta_0 = P(F)_0 P(FD)_0 P(FI_i)_0 \{(Asp)\ [CLI + CLR + CS_{0I} + \overline{CG}_I] + (1 - Asp)$$
$$[(v)\ [CLI + CLR + CS_{0I} + \overline{CG}_I] + (1 - v)(CMF)]\}$$

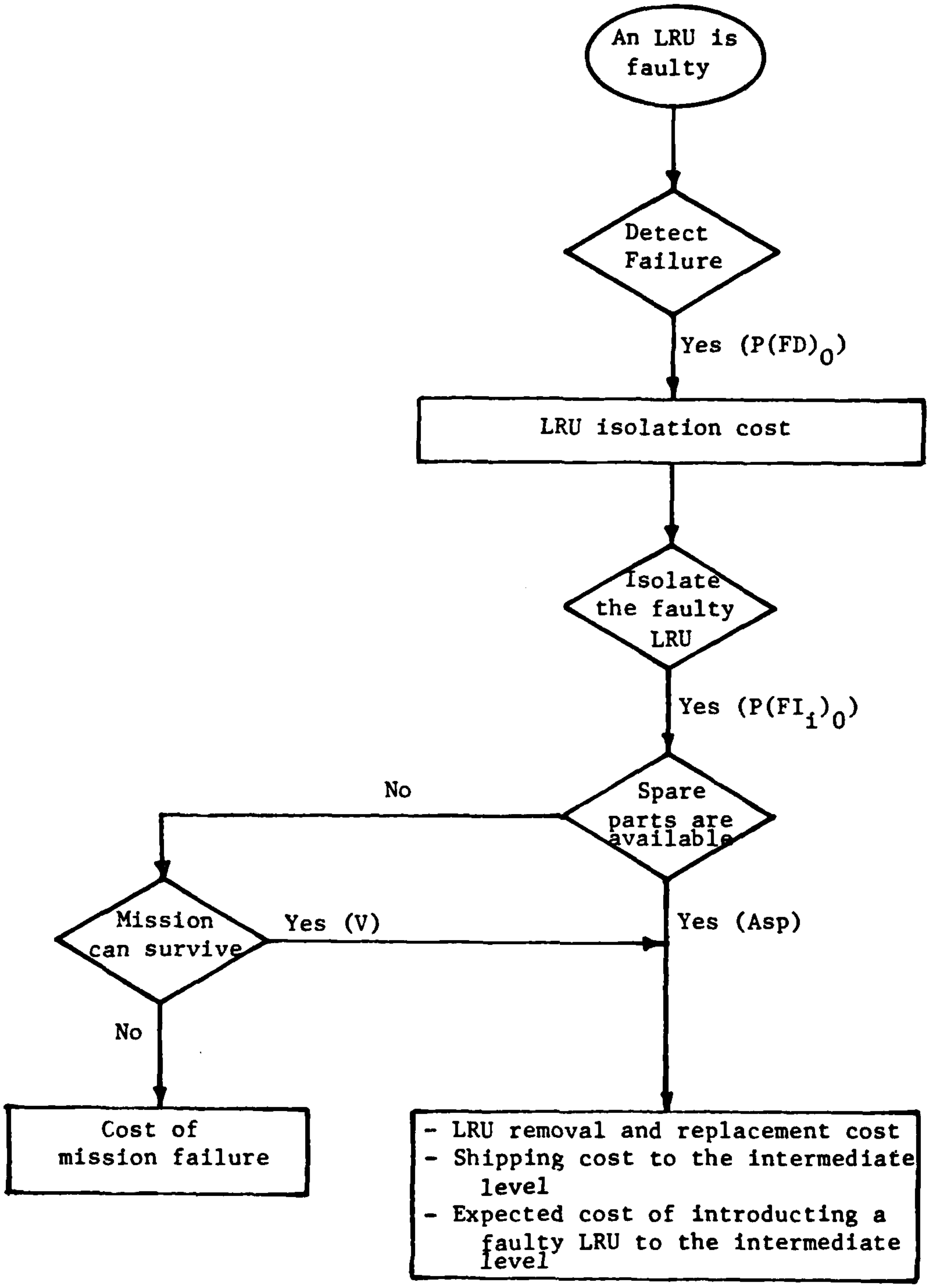

Figure 4.8: Costs Associated with Successful Performance at the Organizational Level

4.4.6 Life Cycle Cost of the Equipment/System

Every time the Equipment/System is used the following costs are involved:

1. Cost of a successful performance of the BIT/ATE ($C\delta_0$)

   That includes all the expected costs of correctly detecting and isolating a failure and the expected cost of introducing a faulty LRU to the intermediate level with other possibilities of introducing a good or faulty module to the depot. (actual expected values of repairing the system at different levels)

2. Costs associated with α, β, and γ errors ($C\alpha_0$, $C\beta_0$, and $C\gamma_0$)

   That includes all costs which arise from the imperfection of testability of diagnostic systems at different levels with all the consequences such as mission abortion, mission failure, introducing a good LRU to the intermediate level as a result of false removal, etc.

A *very realistic figure* of the expected operating and maintenance costs of the equipment/system (C_1) can be modeled by multiplying the above costs ($C\alpha_0 + C\beta_0 + C\gamma_0 + C\delta_0$) by the number of times the equipment/system will be in operation during its life time (number of missions for example). This cost represents all operation and maintenance costs and includes implicitly failure rate of the equipment and time to repair and costs resulting from the imperfection of testability at different levels.

Now, in order to find the expected life cycle costs of the equipment/system, the above cost (C_1) should be added to all one time costs such as initial cost of the equipment, implementation cost of the BIT/ATE system, technical manuals, attrition training, in addition to maintenance material, operations facility space, etc.

4.5 Costs Associated with α, β, and γ Errors for the Composite Organizational/Intermediate System

In this section costs associated with all types of errors α, β, and γ for the composite organizational/intermediate system are presented, computed, and used to develop a new cost-measure of effectiveness.

4.5.1 Expected Cost of α Error ($C\alpha_{OI}$)

Costs associated with α error are presented in Figure 4.9,

$$
\begin{aligned}
C\alpha_{OI} = {} & [1-P(F)_O]\cdot P(FA)_O\cdot P(WI_i)_O\cdot P(FA)_I\cdot P(WI_i)_I \; \{[Asp + V(1-Asp)][CLI + \\
& CLR + CS_{OI} + CMD + CMI + CMR + D_I(CMT) + (1-D_I)(CS_{ID} + \overline{C}_D)] + \\
& (1-Asp)\,(1-V)\,[CMA + CLI + CLR + CS_{OI} + CMD + CMI + CMR + D_I\,(CMT) + \\
& (1-D_I)\,(CS_{ID} + \overline{C}_D)]\}
\end{aligned}
$$

4.5.2 Expected Cost of β Error ($C\beta_{OI}$)

Costs associated with β error are presented in Figure 4.10 where

$$
\begin{aligned}
C\beta_{OI} = {} & P(F)_O \cdot [1-P(FD)_O]\,(1-V)\,(CMF) \\
& + P(F)_O \cdot P(FD)_O\,[1-P(FI_i)_O](1-V)(CLI + CMF) \\
& + P(F)_O\cdot P(FD)_O\,P(FL_i)_O\,[1-P(FI_i)_O[1-P(FA)_I](V)[(1-Asp)(CMA + CLI + CLR \\
& + 2CS_{OI} + CMD) + Asp(CLI + CLR + 2CS_{OI} + CMD)] \\
& + P(F)_O \cdot P(FD)_O \cdot P(FL_i)_O \cdot P(FA)_I[1-P(WI_i)_I]\,(V)[(1-Asp)(CMA + CLI \\
& + CLR + 2CS_{OI} + CMD + CMI) + Asp(CLI + CLR + 2CS_{OI} + CMD + CMI)] \\
& + P(F)_O \cdot P(FD)_O \cdot P(FL_i)_O \cdot P(FA)_I \cdot P(WI_i)_I\,(V)[(1-Asp)(CMA + CLI \\
& + CLR + CS_{OI} + CMD + CMI + CMR + D_I\,(CMT) + (1-D_I)(CS_{ID} + \overline{C}_D)) \\
& + Asp\,(CLI + CLR + CS_{OI} + CMD + CMI + CMR + D_I\,(CMT) \\
& + (1-D_I)(CS_{ID} + \overline{C}_D))] \\
& + P(F)_O \cdot P(FD)_O \cdot P(FI_i)_O \cdot [1-P(FD)_I][CLI + CLR + 2CS_{OI} + CMD + \overline{CF}_O]
\end{aligned}
$$

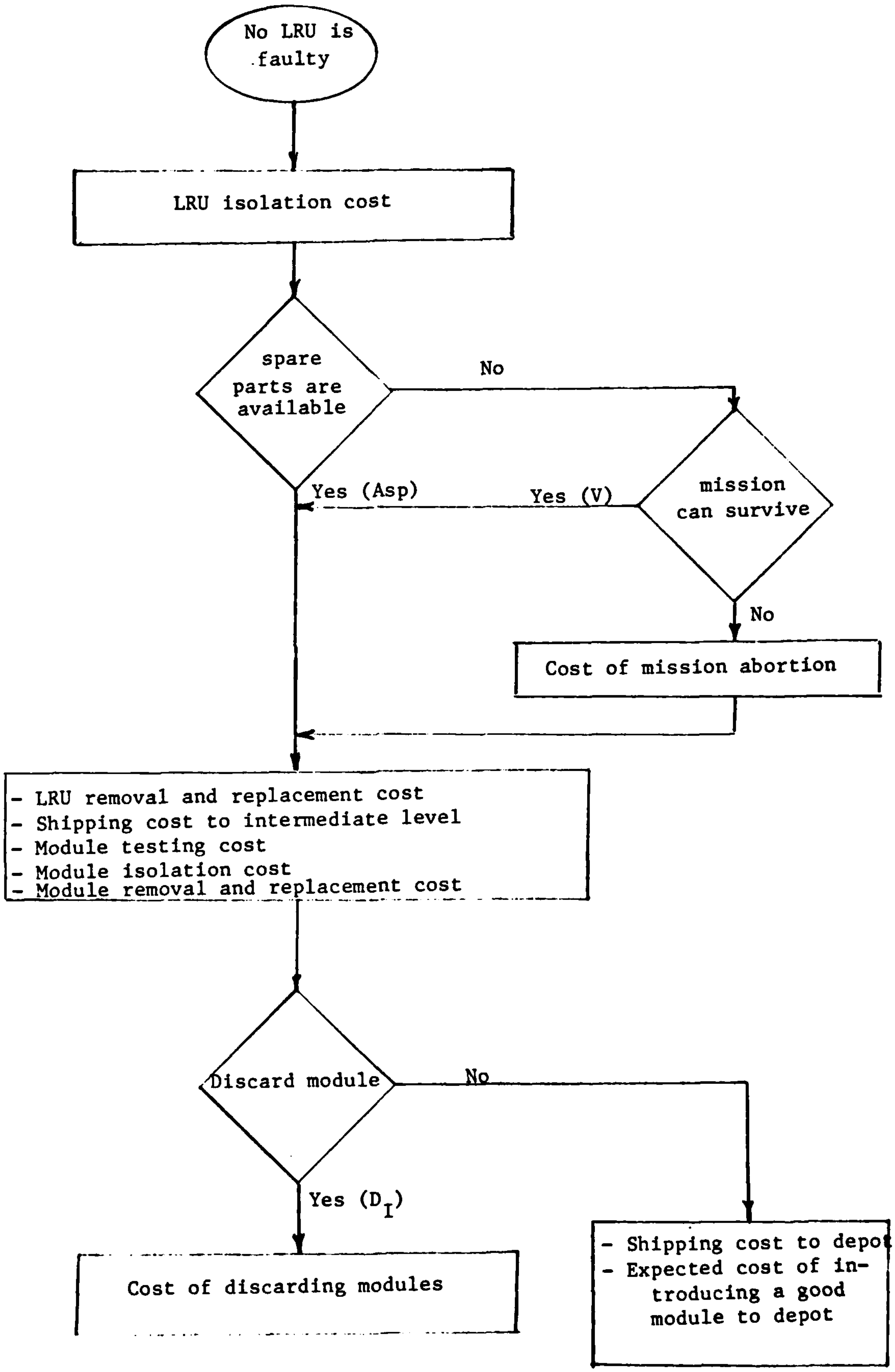

Figure 4.9 Costs Associated with α Error for the Composite Organizational/Intermediate System

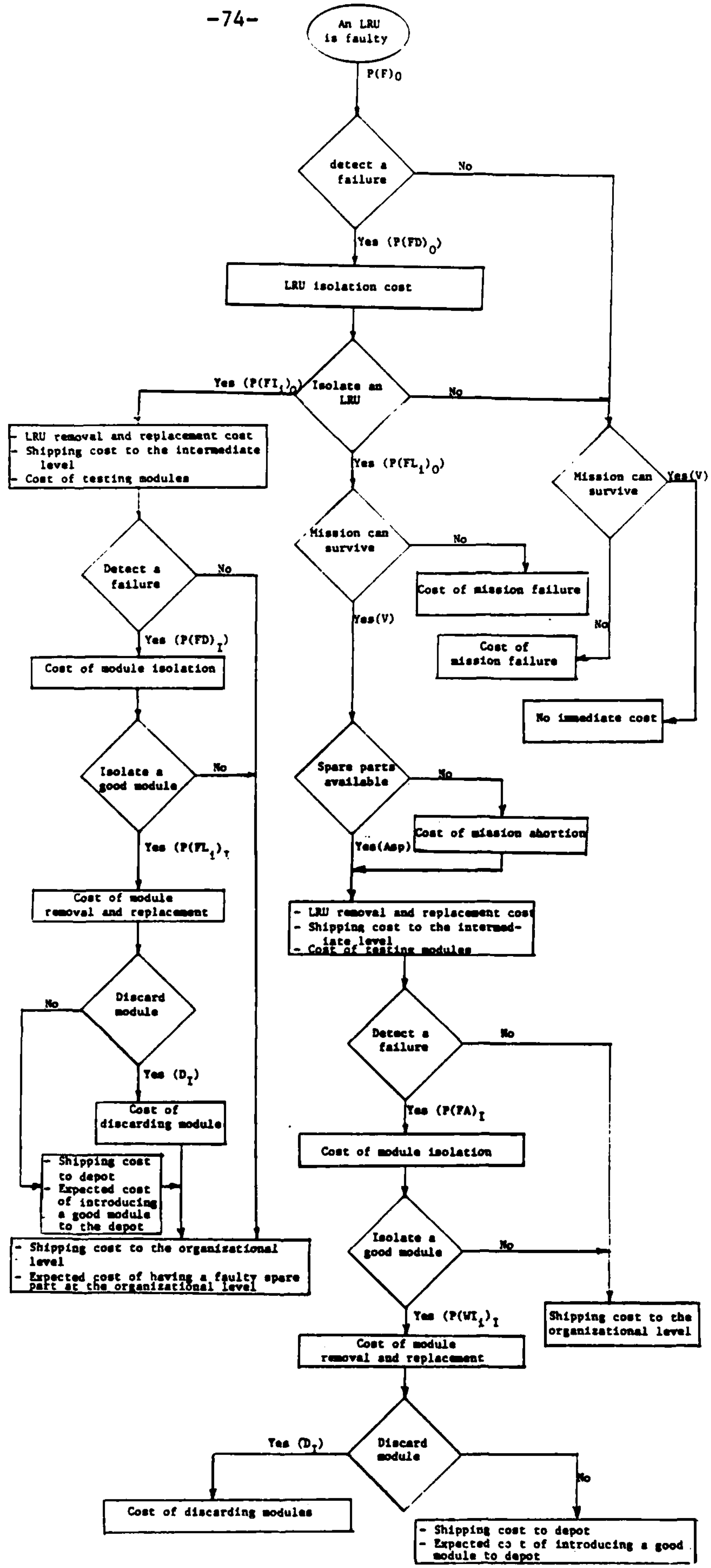

Figure 4.10 Costs Associated with β Error for the Composite Organizational/Intermediate System

$$+ P(F)_O \cdot P(FD)_O \cdot P(FI_i)_O \cdot P(FD)_I \cdot [1-P(FL_i)_I - P(FI_i)_I][CLI + CLR + 2CS_{OI} + CMD + CMI + \overline{CF}_O]$$

$$+ P(F)_O \cdot P(FD)_O \cdot P(FI_i)_O \cdot P(FD)_I \cdot P(FL_i)_I\ [CLI + CLR + 2CS_{OI} + CMD + CMI + CMR + \overline{CF}_O + D_I(CMT) + 1-D_I)(CS_{ID} + \overline{C}_D)]$$

4.5.3 Expected Cost of γ Error ($C\gamma_{OI}$)

Costs associated with γ error are presented in Figure 4.11 where

$$C\gamma_{OI} = [1-P(F)_O] \cdot P(FA)_O \cdot [1-P(WI_i)_O][CLI + (CMA) \cdot P(MA))]$$
$$+ [1-P(F)_O] \cdot P(FA)_O \cdot P(WI_i)_O[1-P(FA)_I] \cdot [(Asp + (V)\ (1-Asp)) \cdot (CLI + CLR + 2CS_{OI} + CMD) + (1-Asp)\ (1-V)\ (CMA + CLI + CLR + 2CS_{OI} + CMD)]$$
$$+ [1-P(F)_O] \cdot P(FA)_O \cdot P(WI_i)_O \cdot P(FA)_I \cdot [1-P(WI_i)][(Asp + (V)\ (1-Asp)) \cdot (CLI + CLR + 2CS_{OI} + CMD + CMI) + (1-Asp)\ (1-V)\ (CMA + CLI + CLR + 2CS_{OI} + CMD + CMI)]$$

4.5.4 Cost-Measure of Effectiveness for the Composite Organizational/Intermediate System

Using the costs associated with α, β, and γ errors for the composite organizational/intermediate system, and the probability of their occurences a new cost-measure of effectiveness can be derived by computing the expected cost of the errors of the diagnostic system ($\overline{C}_{OI}$), where $\overline{C}_{OI} = C\alpha_{OI} + C\beta_{OI} + C\gamma_{OI}$.

5. System Diagnosis Model

The system diagnosis can be modeled using Markov transition matrix. This matrix describes the actual transitions of the system taking into consideration the imperfection of the diagnostic system and all the resulting errors.

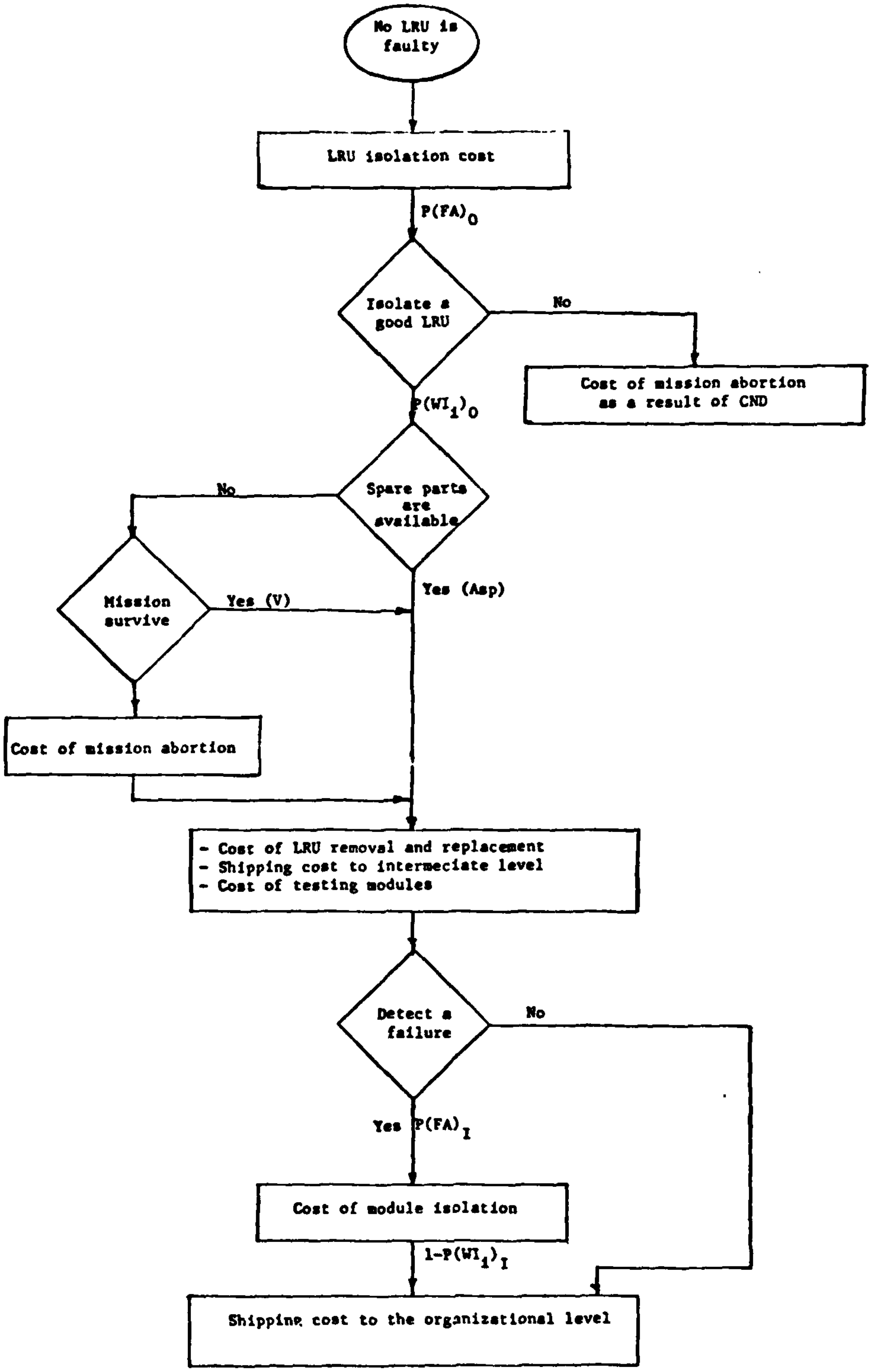

Figure 4.11 Costs Associated with Y Error for the Composite Organizational/Intermediate System

In general, the system can be in one of the following states:

State 0: Equipment is good (diagnostic system does not report any failure|equipment is good)

State 1: Equipment is faulty and failure is not diagnosed (no detection or isolation of failure)

State 2: Equipment is faulty and the failure is correctly detected

State 3: Equipment is faulty and the faulty LRU is correctly isolated

State 4: Equipment is faulty and a good LRU is mistakenly isolated (false isolation)

State 5: Equipment is good but the diagnostic system reports a failure (false alarm)

State 6: Equipment is good but the diagnostic system mistakenly isolates a good LRU (false report).

Let

λ = failure rate of the equipment

λ_f = false alarm rate

λ_d = rate of correct detection (given that there is a failure)

λ_{fi} = rate of correctly isolating the faulty LRU if the failure has been detected

$\lambda_{f\ell}$ = rate of mistakenly isolating a good LRU if a fault is detected in a faulty equipment

μ = rate of removing and replacing LRUs (rate of repair)

λ_{ni} = rate of isolating no LRUs after detecting a failure|equipment is faulty

λ_{fr} = rate of isolating a good LRU after mistakenly reporting a failure (false alarm)

= [rate of false report|false alarm]

λ_c = [rate of CND|false alarm]

= rate of isolating no LRUs after mistakenly reporting a failure (false alarm)

5.1 Transition Probabilities

At State 0

Equipment is good (diagnostic system does not report any failure|equipment is good). If the system is in state 0 at time t, it can make one of the following transitions in t, t+dt:

1 - a transition to state 1 if the equipment fails with probability λdt

2 - a transition to state 5 if the diagnostic system reports a failure (false alarm) with probability $\lambda_f dt$.

3 - remain in state 0 if no failure or false alarm occurs with probability $1 - \lambda dt - \lambda_f dt$

At State 1

Equipment is faulty and failure is not diagnosed (no detection or isolation of failure). If the system is in state 1 at time t, it can make one of the following transitions in t, t+dt:

1 - a transition to state 2 if the diagnostic system detects the failure with probability $\lambda_d dt$

2 - remain in state 1 if the diagnostic system does not detect the failure with probability $1 - \lambda_d dt$

At State 2

Equipment is faulty and the fault is correctly detected. If the system is in state 2 at time t, it can make one of the following transitions in t, t+dt:

1 - a transition to state 3 if the faulty LRU is correctly isolated with probability $\lambda_{fi}dt$

2 - a transition to state 4 if a good LRU is mistakenly isolated (false isolation) with probability $\lambda_{f\ell}dt$

3 - a transition to state 1 if no LRU is isolated with probability $\lambda_{ni}dt$

4 - remain in state 2 if none of the above occurs with probability $1 - \lambda_{fi}dt - \lambda_{f\ell}dt - \lambda_{ni}dt$

At **State 3**

Equipment is faulty and the faulty LRU is correctly isolated. If the system is in state 3 at time t, it can make one of the following transitions in t, t+dt:

1 - a transition to state 0 if the equipment is repaired by removing the isolated faulty LRU and replacing it with a good one with probability μdt

2 - remain in state 3 if the repair is not completed with probability $1 - \mu dt$

At State 4

Equipment is faulty and a good LRU is mistakenly isolated (false isolation). If the system is in state 4 at time t, it can make one of the following transitions in t, t+dt:

1 - a transition to state 1 if the good LRU is removed and replaced by another LRU (the equipment still faulty) with probability μdt

2 - remain in state 4 if the unnecessary repair is not completed with probability $1 - \mu dt$

At State 5

Equipment is good but the diagnostic system reports a failure (false alarm). If the system is in state 5 at time t, it can make one of the following transitions:

1 - a transition to state 1 if the equipment fails with probability λdt

2 - a transition to state 0 if the diagnostic system does not isolate any failure (CND) with probability $\lambda_c dt$

3 - a transition to state 6 if the diagnostic system isolates a good LRU with probability $\lambda_{fr} dt$

4 - remain in state 5 if none of the above occurs with probability $1 - \lambda dt - \lambda_c dt - \lambda_{fr} dt$

At State 6

Equipment is good but the diagnostic system mistakenly isolates a good LRU (false report). If the system is in state 6 at time t, it can make one of the following transitions:

1 - a transition to state 0 if the isolated LRU is removed and replaced by another good LRU with probability μdt

2 - remain in state 6 if the unnecessary repair is not completed, with probability $1 - \mu dt$

Therefore, the Markov transition matrix is

$$
\begin{array}{c}
 \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6
\end{array}
\begin{array}{c}
\begin{array}{ccccccc} 0 & 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\
\begin{pmatrix}
1-\lambda-\lambda_f & \lambda & 0 & 0 & 0 & \lambda_f & 0 \\
0 & 1-\lambda_d & \lambda_d & 0 & 0 & 0 & 0 \\
0 & \lambda_{ni} & 1-\lambda_{fi}-\lambda_{f\ell}-\lambda_{ni} & \lambda_{fi} & \lambda_{f\ell} & 0 & 0 \\
\mu & 0 & 0 & 1-\mu & 0 & 0 & 0 \\
0 & \mu & 0 & 0 & 1-\mu & 0 & 0 \\
\lambda_c & \lambda & 0 & 0 & 0 & 1-\lambda-\lambda_c-\lambda_{fr} & \lambda_{fr} \\
\mu & 0 & 0 & 0 & 0 & 0 & 1-\mu
\end{pmatrix}
\end{array}
$$

and the corresponding Markov transition diagram is presented in Figure 5.1.

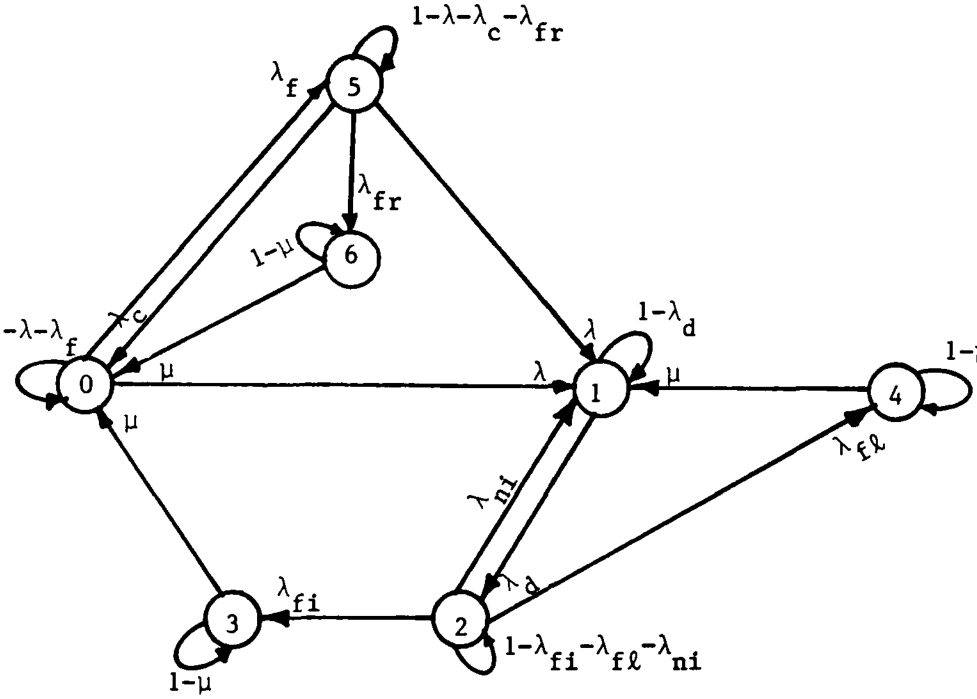

Figure 5.1 Markov Transition Diagram

Using the above model, many properties of the system can be determined. Some of them are:

1) $P_i(t) \equiv$ probability that the system can be in any state i at time t

2) steady state probability, P_i, which is the probability that the system can be in any state i in the long run, or the proportion of time the system spends in each state.

3) Availability $A(\infty)$ = steady state availability = $\sum_j P_j$, $j \equiv$ all acceptable states

4) Reliability function at any time t, $r(t) \equiv \sum_j P_j(t)$, $j \equiv$ all acceptable states [in case the failure state is an absorbing state]

5) Mean time to Failure (MTTF)

6) Maintainability by using the mean recurrence time (length of time to return to an acceptable state from a failed state)

All the above properties of the Markov Process can be very valuable tools in the evaluation of the actual performance of testability considering the imperfections of the diagnostic systems. Currently the work is progressed in this direction to study thoroughly all these properties and tie up the states of the system together in a dynamic fashion with the costs associated with all errors of testability. This approach, hopefully, will lead to a very efficient way to determine and evaluate different testability policies.

6. Summary and Conclusions

6.1 Summary

A multi-level maintenance tier testability evaluation model is developed. This model evaluates analytically the testability parameters at the organizational, intermediate, and the depot levels. In addition, it describes three measures of effectiveness of the performance of the multi-level testability systems taking into account the imperfections of the diagnostic system (false alarms, Can Not Duplicate, and Retest Okay).

Furthermore, all costs associated with the errors of the diagnostic system are developed and modeled to express the effectiveness of the diagnostic system. These costs are also used to predict the life cycle cost for the equipment taking into account the actual performance of the diagnostic system and the resulting consequences of its imperfections.

6.2 Conclusions

Several conclusions can be drawn from this research regarding the performance models of testabilities. They are:

1. Testability parameters, at different levels, are analyzed and evaluated in order to accurately represent the actual performance of diagnostic systems and measure the reliability of the system in accordance with a multi-level maintenance plan. In addition, analytical models are developed to compute these testability parameters.
2. A multi-parameter testability evaluation model is developed. It contains all levels of maintainability parameters at the organizational, intermediate, and depot levels. This model is based on three measures of effectiveness which show the real accuracy and precision of the diagnostic system and cover all imperfections of the diagnostic system such as false alarm, incorrect isolation, failure to detect, CND, etc. These measures could be used as an efficient tool to assess and evaluate the performance of any diagnostic system at one or more levels of repair. In addition, costs of testability and its recourse are impeded in the evaluation model. Considering costs in the model is utilized to find the life cycle cost of any system which considers the costs of the imperfection of the diagnostic system as well as the costs of the resulting consequences like mission abortion or mission failure.
3. System availability, reliability, and maintainability could be assessed more accurately by including false alarm and other imperfections of the diagnostic system.
4. For future works, it is suggested to utilize the Markov transition matrix to investigate the interaction between different states of the system in a dynamic fashion. Availability, reliability, and maintainability of the ssytem

can be determined from the properties of the transition matrix. These properties can be incorporated in an optimization model to find the optimal values of testability parameters which maximizes system reliability.

REFERENCES

Aly, A.A., "Optimal Design of Built-in-Test Diagnostic Systems," A final report submitted to AFOSR under Contract No. F49620-79-0038 (1979).

Aly, A.A., "Optimum Testing Procedures for System Diagnosis and Fault Isolation," University of Oklahoma, School of Industrial Engineering, Final Technical Report submitted to AFOSR under Contract No. AFOSR-80-0139 (1980).

Aly, A.A., and Elsayedaly, E.A., "An Efficient Algorithm for Optimal Design of Diagnostics," University of Oklahoma School of Industrial Engineering, Technical Report No. 81-3, Norman, OK (1981).

Aly, A.A., and Bredeson, J.G., "Analytical Procedures for Testability," RADC-TR-83-4, Final Technical Report (1983).

Aly, A.A., and McDonald, K.L., "Optimal Testing and Packaging Design for Diagnosis of Digital Systems," University of Oklahoma, School of Industrial Engineering, Technical Report No. 83-7, Norman, OK (1983).

Biegel, J.E. and Bulcha, B., "Multilevel Modularization of Systems to Minimize Life Cycle Cost," RADC-TR-78-207, Final Technical Report (1978).

Biegel, J.E., A Multilevel Modularization Technique Designed to Minimize Life Cycle Costs for Large Systems," **AIIE Proceedings Spring Annual Conference**, (1979).

Bogard, D.R. et al., "Operation and Support Cost Characteristics of Testers and Test Subsystems," RADC-TR-79-334, Final Technical Report (1980).

Butterworth, T., "Some Reliability Fault Testing Models," **Operations Research**, Vol. 20, (1972).

Caponecchi, A.S., A Methodology for obtaining solutions to the Modular Design Problem, unpublished Ph.D. dissertation, The University of Texas at Austin, Austin, Texas (1971).

Chang, Herbert Y., "Figures of Merit for the Diagnostic of a Digital System," **IEEE Transactions on Reliability**, Vol. R-17 (1968), pp. 147-153.

Cohn, M. and Ott, G., "Design of Adaptive Procedures for Fault Detection and Isolation," **IEEE Transactions on Reliability**, Vol. R-20, (1971), pp. 7-10.

Conley, G., "Digital System Diagnostics - Design/Evaluations," **Proeccedings of the Annual Reliability and Maintainability Symposium** (1980).

Firstman, S., and Gluss, B., "Optimum Search Routines for Automatic Fault Location," **Operations Research**, Vol. 8 (1960).

Gaertner, W.W., "Development of BIT Equipment for Tactical FM Radios," Army Electronics Command, AD: A005277.

AD-A146 255 PERFORMANCE MODELS OF TESTABILITY(U) OKLAHOMA UNIV NORMAN SCHOOL OF INDUSTRIAL ENGINEERING A A ALY AUG 84 N00019-83-C-0327 2/2

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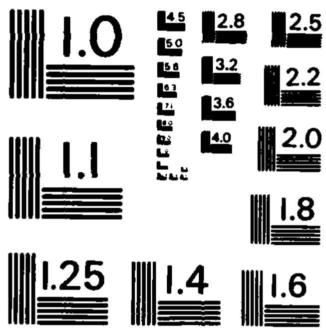

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Gleason, D., "A Measure of BIT/ETE Effectiveness," A working paper, USAF, RADC/RBET, Griffis AFB, Rome, New York (1981).

Gluss, B., "An Optimum Policy for Detecting a Fault in a Complex System" **Operations Research**, Vol. 7 (1959).

Halpern, Jonathan, "A Sequential Testing Procedure for a System's State Identification," **IEEE Transactions on Reliability**, Vol. R-23 (1974), pp. 267-272.

Heckelman, R.W., et al., "Self Diagnosing Design Techniques," General Electric, Publication Number AFAL-TR-78-183 (1981).

Horkovich, James A., "Automatic Fault Detection/Fault Isolation Systems: Requirements and Testing," AFTEC Logistics Assessment Procedures Division, Kirtland AFB (1981).

Johnson, Richard A. and Brulé, John D., "Diagnosis of Equipment Failures, RADC-TR-60-67A, Final Technical Report, (1960).

Kletsky, E.J., "Diagnosis of Equipment Failures," RADC-TR-60-67B, Final Technical Report, Part 2/2, (1960).

Levy, Girard W., et al., "Final Report on Improved Maintenance Procedures for Inertial Guidance Systems," PRAM Program Office, AFSC, Aeronautical Systems Division: Wright-Patterson AFB (1976).

Linden, V.L., "Diagnostic Development - A New Prospective," ATE Newsletter (1981).

MIL-STD-721B, "Definition of Effectiveness Terms for Reliability Maintainability, Human Factors, and Safety," Aug. 1966.

Pieper, W.J., et al., "Computer Generated Troubleshooting Trees: Application and Tryout," AD 004634, (1974).

Pliska, T.F., Jew, F.L., Angus, J.E., "BIT/External Test Figures of Merit and Demonstration Techniques." RADC-TR-79-309, Rome, N.Y., (1979).

Sheskin, T.J., "Design of System Diagnostic and Fault Isolation Procedures" USAF/ASEE Summer Faculty Research Program, Vol. 2, AFOSR-TR-78-0349 (1977), AD-A051514.

Sheskin, T.J., "Fault Isolation for Modular Electronic Equipment," **Proeccedings of the Annual Reliability and Maintainability Symposium**, (1979).

Tuttle, D.E. and Loveless, R., "Built-In-Test and External Tester Reliability Characteristics," RADC-TR-80-32, Rome, New York (1980).

Winter, B.B., "Optimal Diagnostic Procedures," **IRE Transactions on Reliability and Quality Control**, Vol. RQC-9 (1960).